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Visualizing the Environmental Impact of Dietary Choices: Exploring an Interactive Mini-World as a Proxy to Communicate Three Planetary Boundaries

Visualiser l'impact environnemental des choix alimentaires : exploration d'un mini-monde interactif comme visualisation mandataire pour communiquer trois limites planétaires

Aymeric Ferron*
aymeric.ferron@inria.fr
Inria
Talence, France

Martin Hachet*
martin.hachet@inria.fr
Inria
Talence, France

Yvonne Jansen
yvonne.jansen@inria.fr
Univ. Bordeaux, CNRS, Inria, LaBRI
Talence, France

ABSTRACT

It can be difficult to extrapolate how decisions made in our daily lives impact the environment in the long term. While rich data and many calculator tools are freely available, comparing how different choices add up over time remains a complex and tedious task. In this paper, we focus on the specific case of dietary habits and explore how long-term consequences of different dietary choices may be communicated using a mini-world as a proxy, where decisions of one person affect the entire mini-world. We focus on three planetary boundaries: climate change, global freshwater use and land system change. After describing the prototype, we report insights from interviews conducted with three experts who tested it. The results suggest that the mini-world has potential for facilitating the comparison of environmental consequences linked to dietary habits. At the same time, numerous improvements have also been proposed.

RÉSUMÉ

Il peut être difficile d'extrapoler l'impact à long terme sur l'environnement des décisions prises dans notre quotidien. Bien que de nombreux outils de calcul soient disponibles, comparer la façon dont différents choix s'additionnent au fil du temps reste une tâche complexe. Dans cet article, nous nous concentrons sur le cas spécifique des habitudes alimentaires et explorons comment leurs conséquences à long terme peuvent être communiquées en utilisant un mini-monde comme visualisation mandataire, où les décisions d'une personne affectent l'ensemble du mini-monde. Nous nous concentrons sur trois limites planétaires : le changement climatique, l'utilisation de l'eau douce et la modification de l'usage des sols. Après avoir décrit le prototype, nous présentons les résultats des entretiens menés avec trois experts l'ayant testé. Les résultats suggèrent que le mini-monde a le potentiel de faciliter la comparaison des conséquences environnementales liées aux habitudes alimentaires. Dans le même temps, de nombreuses améliorations ont été proposées.

CCS CONCEPTS

• **Human-centered computing** → **Visualization**; **Human computer interaction (HCI)**.

KEYWORDS

Data visualization, Exploranation, SHCI

MOTS CLÉS

Visualisation de données, Explorication, IHM Soutenable

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1 INTRODUCTION

Complex systems are complicated to understand by nature. Scientists use models and data to describe them, but non-experts or learners often struggle to understand them [29]. The biosphere is one such complex system. The Intergovernmental Panel on Climate Change (IPCC) has been raising the alarm since 1988 that the lifestyle of some countries and people around the world is not sustainable, including in their last synthesis report published in 2023 [31]. Lifestyles are termed unsustainable if they result, even over time, in exceeding so-called planetary boundaries, such as when emitting more greenhouse gas (GHG) than the earth can absorb, or when the use of freshwater continuously exceeds the annual replenishment of freshwater [49]. Consequences of unsustainable lifestyles, such as climate change, which increases the frequency and severity of forest fires, heat waves, or flooding, are starting to be felt even in high-emitter societies, but lifestyles are changing

*Bivwac, LaBRI, Univ. Bordeaux, Bordeaux INP, CNRS

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slower than necessary to respect the Paris Agreement aiming for carbon neutrality[1] by 2050 [55].

There are many possible pathways to environmental sustainability, but as a complex system, these are not necessarily straightforward to recognize and understand. Developing explanatory designs can be beneficial to enlighten all the different subsystems of the huge field of environmental impacts. Agriculture and food consumption is one such subfield worth exploring. In 2018, 26% of the global GHG emissions were emitted by food production [47]. Among these GHGs, 61% were due to livestock through direct emissions, and land use and crops to feed them [47]. Thus, reducing animal-based-product consumption is an efficient choice to mitigate our daily impact on the environment. Scarborough et al. report that a plant-based diet has only half the environmental impact of one including frequent meat consumption, and often close to a quarter for some other environmental indicators such as freshwater consumption [51]. But do all sustainable pathways require that everyone on earth changes to a vegan lifestyle?

Human-Computer Interaction (HCI), and more specifically Sustainable HCI (SHCI), have focused on creating designs to raise awareness about sustainability. A lot of *eco-feedback* displays were created during the last two decades, many focusing on energy consumption [5, 24, 44, 45, 54]. This approach also garnered criticism because of its tendency to consider people as the problem and not as part of the solution [16]. More recently, the concept of *exploranation* has been coined by Ynnerman et al. [56] as a new way to raise awareness by including people in a reflective, conscious and respectful learning and understanding process. The approach aims to enable people to explore the same data that experts work on, but in an accessible way, combining exploratory and explanatory visualizations which guide people in their exploration of the data.

This paper explores how an exploranation approach may enable people to explore and compare the impact of dietary choices on three planetary boundaries: climate change, global freshwater use and land system change. Building on food environmental data, we explore these data using a mini-world as a mapping, which reflects the effects of GHG emissions, land use and water use as a result of dietary habits. The mini-world paradigm we introduce in this paper is a way to use the concrete and vivid origin of the data to encode it in its expected consequences on the real world. To our knowledge, we are the first to explore such a visualization. After introducing this visualization, we report interviews with three experts in scientific outreach and environmental science about the potential of the prototype. Our contributions are (1) an exploration of a new kind of visualization and (2) insights from experts concerning the opportunities and challenges of this genre of visualization.

2 RELATED WORK

2.1 Human impact on the environment

The impact humankind has on the environment is complex. It has received a specific attention since 1988, the year of the foundation of the Intergovernmental Panel on Climate Change (IPCC), which reviews the scientific literature on climate change and evaluates the strength of evidence for each finding to provide policymakers with relevant knowledge about climate change. IPCC reports summarize the complex causes and consequences related to climate change and let stakeholders know about scientific literature. The reports' conclusions are often used by journalists to communicate to citizens, but even simplified, these scientific statements and graphs can be difficult to understand for some [26].

In addition, climate change is not the only environmental issue humankind has to face. Indeed, eight other issues have been identified in 2009 by Rockström et al., who termed them *planetary boundaries* [49]. According to the authors, planetary boundaries are "*boundaries within which [...] humanity can operate safely. Transgressing one or more planetary boundaries may be deleterious or even catastrophic due to the risk of crossing thresholds that will trigger non-linear, abrupt environmental change within continental- to planetary-scale systems*". In 2023, Richardson et al. reported that six boundaries are already transgressed among the nine and two more are threatened [46].

Eating food is a common action done multiple times a day and which impacts all the planetary boundaries [42]. More precisely, food and agriculture are responsible for approximately 26% of the global GHG emissions, 50% of land use, 70% of freshwater withdrawals and 78% of eutrophication according to Ritchie et al. [48]. Improving the environmental impacts of the food system is thus a major concern. The impact food has on the environment has been well studied, especially with the Life Cycle Assessment methodology (LCA). With this method, 16 indicators are examined to determine as precisely as possible the impact food has on the environment, from the agriculture stage to the consumption one. Results of this analysis are available on Agribalyse for French food items, a database maintained by ADEME, a French government agency.

2.2 Sustainable HCI and eco-feedback technologies

Within HCI, a growing number of publications has been published over the past 20 years, concerned with the question of how interaction design may contribute to transition to more sustainable lifestyles. Notable examples are Blevis' 2007 proposal of *sustainable interaction design* [7], and the rich literature exploring the principle of eco-feedback, defined by Froehlich et al. as "*technologies that provide feedback on individual or group behaviours with a goal of reducing environmental impact*" [22]. Such technologies focused a lot on energy consumption (see [5, 24, 44, 45, 54]), but eco-feedback applications also explore other sustainable practices, such as encouraging composting [36], supporting the transition to a vegan diet [12], raising awareness about CO_2 emissions related to taxi trips [39] or about water and energy consumption of one's laundry [23].

However, the global society is composed of diverse sets of individuals, states, companies, and associations. Each of the former has their own agenda, and priorities differ from one to another, often with conflicting (short-term) interests. Thus focusing solely on actions by individuals, as eco-feedback applications commonly do, is not sufficient. DiSalvo et al. discussed this issue in 2010 and highlighted that 70% of feedback technologies targeted individuals [16]. Similarly, Brynjarsdottir et al. argued in 2012 that a focus on persuasive eco-feedback designs was narrowing the vision of

[1]Carbon neutrality refers to respecting the planetary boundary for GHG emissions, that is, not emitting more than the available carbon sinks can absorb.

Sustainable HCI (SHCI) researchers by simplifying the system in a problematic way [11]. In light of such critiques, SHCI shifted its focus over the last decade, to explore how to take a more systemic approach [9] favouring awareness and reflection, through which users are enabled to learn and to discover the systemic aspects of environmental impacts.

Within the context of food production and consumption, the concept of *food environment* has been developed to describe individual's behaviour within the society when choosing and eating food. Downs et al. expand the food environment concept as follows: "*the consumer interface with the food system that encompasses the availability, affordability, convenience, promotion and quality, and sustainability of foods and beverages in wild, cultivated, and built spaces that are influenced by the socio-cultural and political environment and ecosystems within which they are embedded*" [17]. Within the food environment system, Brocard and Saujot define four environments: (1) a physical environment which refers to the spatial organization of infrastructure selling food, (2) a socio-cultural environment which refers to the social norms and constructs around food, (3) an economic environment which includes financial resources reserved for food, and (4) a cognitive environment which refers to the knowledge and skills consumers have to make decisions around food [10]. The concept of food environments is useful to illustrate the complexity of choosing a meal, which depends on a lot more than simple individual factors.

2.3 Exploranation

There is a stated interest in the French society about climate change. According to a survey conducted by the Descartes Foundation in 2023 with 2000 representative French citizens, 49.3% of the population is "*extremely interested*" or "*very interested*" about information and news about climate change [15]. However, the same survey shows that people are overall discontent about the way media communicate about the topic, indicating a lack of concreteness and a lack of educational content.

One approach to address such a need is the concept of *exploranation*, proposed in 2018 by Ynnerman et al., which combines exploratory visualization and explanatory visualization [56]. This approach is meant to allow lay people to explore real data sets and support them in making sense of it. An example application of exploranation is the work of Besançon et al. concerning data linked to climate change and to environmental food impact [6]. People are invited to compose meals and to explore their environmental consequences illustrated through bar chart visualizations. By comparing different food products, people can discover their environmental impacts. Another food-related project is Carbon Scales which is a prototype encoding GHG emissions of food through the weight of tokens [38]. Using data physicalization, this project allows users to test their knowledge about food impact by trying to allocate a carbon footprint to different food products and for different life cycle steps. By proceeding with trials and errors, users are invited to explore what they think about the carbon footprint of food, and to learn from the correct answers. Such kind of designs allow people to freely explore possibilities without any feedback or value judgment concerning their own personal behaviours. Lay people can explore data and extract knowledge from the design.

In this article, we explore the concept of exploranation in the context of proxy-visualizations in a mini-world paradigm.

2.4 Data visualization beyond bar charts

Data allow learning about a lot of topics. With databases, we are able to describe many objects or phenomena. However, figures and charts can be abstract and may not be engaging for everyone. For example, Bao et al. compared different ways to show resource consumption behaviour in order to understand the impact of figures as "quantitative clarity of information" and the impact of visual effects as "strength of emotion" [4]. Focusing on eco-feedback visualizations, the authors report that both figures and pictures were found effective as displaying environmental data, but people with a major in non-technical topics preferred emotional visualizations. Others argue that measurements can be difficult to grasp because of their abstraction quality and suggest using more concrete ways to visualize data [40]. Expanding on this, Chevalier et al. introduce the concept of *concrete scale visualizations* which encode data through familiar objects or locations in order to make data "more concrete" [14]. For example, in the film *New York's carbon emissions*, 54 million metric tons of CO_2 are shown as balls, covering the Empire State Building with them [41]. A similar direction was explored by Assor et al. with ARWav, an augmented reality application displaying accumulated quantities of trash bags, water, and coffee cups [2].

Relatedly, Jacob et al. developed the notion of Reality-Based Interaction (RBI) to qualify interactions that use analogies with the real world to make them easier to use [34]. One of the four categories of RBIs is the principle of using "naive physics". It builds on the assumption that "*people have common sense knowledge about the physical world*". In the context of environmental data visualization, we can imagine that most people have at least a naive understanding of climate change and its consequences, since it has become a pervasive topic in the news over the last decades. Furthermore, Baker et al. suggest similar insights by proposing that "*the greater a visual representation's support for analogical reasoning, the better will be its viewer's sense-making experience.*" [3]. Indeed, analogies allow to facilitate knowledge creation by using mental models available in the long-term memory of the user and by making parallels between the situations. Using visualization inspired by reality could be an engaging and innovative way to convey information to non-expert people and to help them build knowledge.

Applying such an approach in the area of food choices, Jach explored a VR environment [33] that immerses users in a virtual city, half buildings and half natural spaces, which changes according to food choices during a fixed scenario. However, the choices proposed are binary and users have to follow a script, limiting their agency. *Climate Game*[2] is a self-logging mobile application for food, transportation and housing, using a cartoon island that changes according to the data entered by users, changing the colour of the sky, the water and the land of the island. *Veganity, your journey* is a serious game [12] using food self-logging allowing the player to spend virtual energy to improve the sustainability of the world by investing in infrastructure in a virtual countryside.

[2] https://climategame.eu/mobileapp/

2.5 Positioning within the Sustainable Development Goals framework

In 2021, Hansson et al. suggested that all work in SHCI should position itself using the United Nations framework for sustainable development, known as the Sustainable Development Goals (SDG) [3], as a possibility to classify the SHCI corpus [25]. This framework is useful to communicate in what extent a work contributes to sustainability worldwide, especially because it is an interdisciplinary framework shared and used by a large number of sustainability stakeholders. As members of the SHCI community, we think that it is relevant to position our work in this framework.

This research aims to contribute to three of the 17 Sustainable Development Goals of the United Nations, namely "4.7: By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles [...]", "12.8: By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature" and "13.3: Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning".

3 DESIGN AND IMPLEMENTATION

Understanding complex systems poses a considerable cognitive effort on learners [29]. We explore an approach in which we simplify the complex system of how dietary choices affect the biosphere by using a proxy visualization (1) focusing entirely on food production, and (2) considering only effects on three planetary boundaries.

3.1 The impact of food on the environment

Assessing the environmental impact of humanity is a complex problem due to the diversity of impacts, of several stakeholders and of computation scope. Food has several impacts on the environment, including impact on climate change through GHG emissions, impact on biodiversity through acidifying processes, eutrophication and land use, impact on environmental health through ozone depletion, ionizing radiation and particulate matters, and impacts on resources through fossil energy, minerals and water consumption. Different frameworks and taxonomies have been proposed to characterize different impacts and indicators and to facilitate tracking their trajectories over time. One such framework is that of planetary boundaries, which considers nine boundaries to not exceed [53]. The French Agency for Ecological Transition (ADEME) uses 16 specific indicators as defined by Fazio et al., including the above [20], which Soler et al. classify into 4 categories (climate, biodiversity, environmental health and resources) based on their main impact [52]. These indicators are used during Life Cycle Assessment analysis (LCA) and are not specific to the food system [27]. In this article, we focus on three of these indicators, which also match planetary boundaries: climate change (due to GHG emissions), global freshwater use, and land system change. Those indicators are considered as the most important by the European Product Environmental Footprint (PEF) methodology with the higher aggregated weights in the method[4].

[3] https://sdgs.un.org/goals

[4] See doc.agribalyse.fr/documentation/les-donnees/methodologie-acv for details.

3.2 Mini-world as a proxy

Building on the concept of Naive Physics from Jacob et al. [34], we imagined ways to encode the data through concrete impacts it has on the environment and for which we can assume that non-experts are at least vaguely familiar with. We decided to use a mini-world paradigm that incorporates some of the fundamental features of the Earth so as to serve as a simplified proxy of this complex system. The mini-world operates as a simulation. It evolves according to the exploranation inputs, following concrete environmental models coming from the scientific community and based on data extracted from a database of a government agency. We chose indicators that were easy to represent and should be known by the general public: climate change, land use and water use. Focusing on only three indicators was a compromise between having a poor visualization focusing on a single indicator and having a too rich mini-world which risks being complicated to design and interact with or containing confusing proxies.

3.3 Data

We use data provided by ADEME in the form of the Agribalyse database[5] which contains environmental information about more than 2500 products. Including all of these would make interaction with a prototype slow and tedious, we therefore selected a variety of food types to enable people to find food similar to what they commonly eat. We picked five different proteins (beef, chicken, fish, pork, plant-based proteins), and one product each for starch (pasta), vegetables (ratatouille), dairy (Greek yogourt) and fruit (fruit salad), as detailed in Table 1 (data accessed in September 2023).

3.4 Mapping data to proxy visualizations

The data needs to be mapped to proxy visualizations to show how the mini-world changes over time in response to the impact that dietary choices have on it. Freshwater use can be mapped to the water level of a lake, and land use can be mapped in a straightforward fashion to the amount of dry surface used for agriculture instead of forests. Mapping climate change to a visible outcome is, however, less obvious. Climate change is due to greenhouse gas emissions which are in themselves invisible. We therefore looked at different consequences of climate change, and selected melting glaciers and sea-level rise to encode the climate change indicator in our mini-world (see more details below).

After choosing the basic mappings, we had to scale them so that certain amounts of emissions or required resources correspond to a change in proxy visualizations in the mini-world. We chose to use a *causal link* to represent these proxy links, i.e. to sum up the different impacts of a meal and to show their impact on the mini-world, throughout the years. To compute the amount of emissions and the use of resources over a year, we use a *five days* meal composition plan to indicate the frequency with which one consumes different food types (as summarized in Table 1). We then map this data as following to proxy visualizations.

Climate change. The climate change indicator represents the *mass of carbon dioxide equivalent* emitted in the atmosphere. It is assumed that the Earth's carbon sinks can absorb roughly 18.2 Gt of CO_2 per year [21] (which is about half of what was emitted in 2021).

[5] https://agribalyse.ademe.fr/

Food item	**Specific food** (hyperlink)	**Climate change** (kg CO_2eq/kg)	**Land use** (Pt/kg)	**Water use** (m^3/kg)
Beef	Flank steak	34.4	2440	6.96
Chicken	Chicken fillet	9.11	404	9.07
Fish	Salmon fillet	7.05	330	1.5
Pork	Pork chop	13	710	9.66
Plant-based protein	Lentils	0.401	63	0.476
Vegetable	Ratatouille	0.98	114	5.87
Starch	Pasta	1.05	97	0.703
Fruits	Fruits salad	1.1	32.4	12.3
Dairy	Greek yogourt	2.11	122	0.488

Table 1: The list of food items chosen from Agribalyse together with the environmental indicators used for this project for each food item. Note that the second column includes hyperlinks to the entry of each food item in the Agrybalise database.

If we divide this carbon budget equally among all 8 billion people, everyone gets a personal budget of about 2.3 tons per year. This number is consistent with the recommendation made by *Carbone 4*, a consulting firm specialized in carbon budgets, in their report "Faire sa part" [18]. Since food is only one of humanity needs, *Carbone 4* suggests allocating 0.6 tons of CO_2 to food production and consumption[6]. We thus use 0.6 tons as the carbon budget available in the mini-world, that is, the mini-world's carbon sinks can absorb up to 0.6 tons. Once this yearly budget is used up, consequences start to accumulate and become visible: (1) the mini-world's glacier melt by 6% per year for each 0.6 t of additional CO_2 emitted, similar to the melt rate observed for the Swiss glaciers in 2022 [30] and (2) the mini-world's sea level increases by 0.1 metres for each additional 0.6 tons of CO_2 equivalent emitted.[7]

Water use. The freshwater use indicator represents the volume of water used during the entire lifecycle of the meals' components. Note that this indicator takes water scarcity at the place of production into account, that is, a food item whose production requires high amounts of freshwater is considered to use more resources if it origins from an area that suffers from water scarcity. We calculate freshwater use based on pre-defined water replenishment in the mini-world, simulating a water cycle with our own water scarcity. We set the yearly water replenishment to 2,011 cubic metres (which corresponds to the average yearly amount of freshwater needed for a vegetarian diet according to data extracted from Table 1) and the initial water volume available in the mini-world to 20,110 cubic metres. Consequently, the mini-world's lake level will vary according to the water consumption induced by meals and according to its water replenishment.

Land use. The land use indicator provided in the Agribalyse database is a multi-factor indicator based on European recommendations aggregating a variety of soil properties (including biotic production, erosion resistance, mechanical filtration, phreatic table replenishment) [57]. These form a quality score allowing computing a "loss of quality" score which also includes area used and duration of use [13]. We simplified this complex measure and make it visible in the form of *land used for agriculture*. As a scaling mechanism, we take the food item with the highest score, beef, and map it to 100% of available land used for agriculture. All other food items are scaled according to this anchor. Consequently, the surface use of the mini-world varies according to meal compositions and is covered in wheat fields when meals have high land use scores or are covered in grass and forests when these are low.

3.5 Implementation

The prototype was developed as an interactive 3D environment using Blender for the individual 3D models of all components and Unity 2021.3.12f1 for the implementation. It runs as a desktop application containing several functionalities. This computational approach allows us to animate and simulate a mini-world in real-time, according to inputs chosen by the users. The prototype is available at this external link.

3.5.1 Views of the mini-world. The prototype includes six different views to explore the mini-world and to see in detail the consequences of different diet habits on the environment. Each of the views facilitates the observation of specific consequences.

The top-down view (Figure 1a) provides an overview over the entire mini-world: the state of the glaciers are clearly visible, and the yellow dots scattered around the island give an overview of where agriculture takes place.

The view focusing on the village near the lake (Figure 1b) illustrates the state of freshwater availability. With freshwater supplies going down, one can see the water level of the lake going down.

The view of the forest (Figure 1c) enables a viewer to tell how intensive agriculture has to be to produce the food currently selected. By default this view shows a forest, but highly demanding diets can turn the forest into agricultural land.

The island view (Figure 1d) provides an indicator for the current sea level. By default, one can see a little beach and cliffs on the side of the island, but with rising waters, the island floods and starts to vanish in the sea.

The beach view (Figure 1e) gives a combined impression of land use (with crops possibly growing near the beach) and sea-level rise (with the beach getting narrower due to rising waters).

Finally, the mountain view allows to inspect the current state of the glaciers (Figure 1f).

3.5.2 Dietary composition. The main interaction takes place in the form of defining a menu. This can be achieved with one of

[6]Note that this allocation methodology is not universally accepted and other models exists (see [28])

[7]See level rises because of two main reasons. First, because of thermal expansion, oceans expand by getting warmer. Second, glacier and ice floe melting increase ocean volume. See https://climate.nasa.gov/news/2680/new-study-finds-sea-level-rise-accelerating/ for more information.

(a) Top-down view (b) Village view (c) Forest view

(d) Island view (e) Beach view (f) Glaciers view

Figure 1: The state of the mini-world can be inspected through six different views.

several graphical menus with varying degrees of complexity. A few pre-defined dietary choices are available as presets (e.g. "100% beef" all year long versus "100% vegetarian" all year long) (cf Figure 6 in the Appendix), and one can compose a more precise menu by entering percentages for the different food types (cf Figure 7 in the Appendix). Instead of entering percentages, it is also possible to enter the composition of ten meals by ticking check boxes accordingly on a third graphical menu (cf Figure 8 in the Appendix). At any moment, a detailed view can be activated to display the current meal composition.

3.5.3 Time management. After composing a menu, the mini-world is updated to reflect the need for food production and consumption and one can move a cursor to move through time and see environmental consequences of the dietary composition sum up, and the visualization is updated accordingly to proxy visualizations described above.

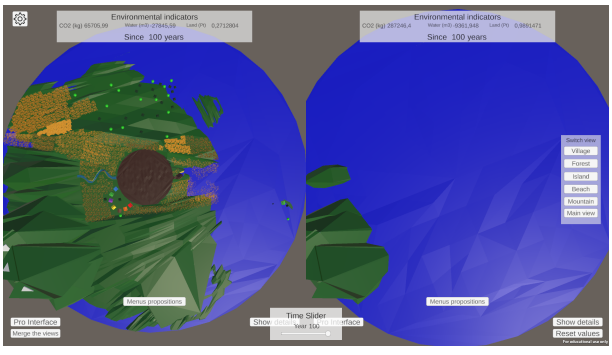


Figure 2: Comparing GHG emissions accumulating in the mini-world's atmosphere after 100 years with a "100% chicken" diet (left) with a "100% beef" diet (right).

3.5.4 Comparison view. It is possible to split the screen and show two mini-worlds in parallel. Using this mode, it is possible to compare side by side the visualization for two different dietary habits, with time being synchronized between them. Figures 2, 4 and 5 show examples of the split screen functionality.

3.6 Exploranation examples

The mini-world can be seen as a simulation representing the planetary boundaries for the Earth, especially concerning GHG emissions and water consumption. If the dietary composition stays within the planetary boundaries, the mini-world does not change—it is in a sustainable equilibrium. However, if the dietary composition exceeds the boundaries, over time the aspect of the representation will change more or less drastically, depending on by how much the planetary boundaries are exceeded. The prototype can therefore be used to compare the extent to which two eating habits respect sustainable limits in terms of carbon emissions, land and water use.

The person interacting with it decides indirectly the state of the mini-world, which is calculated based on the choices made during these interactions. However, at the same time, the design can be interpreted as a mini-world in which the person interacting sets the policies to produce certain types of food more than others. Importantly, the mini-world shows the long-term systemic consequences of such choices or policies. As such, this mini-world encompasses both the individual responsibilities and systemic ones.

In this subsection, we describe some exploranation cases to illustrate the mini-world's behaviours according to specific diets.

3.6.1 Comparing GHG emissions. Since our mini-world acts as a little Earth, it simulates carbon sinks, as we detail in section 3.4. Releasing 0.6 tons of GHG *into the atmosphere* during a year means

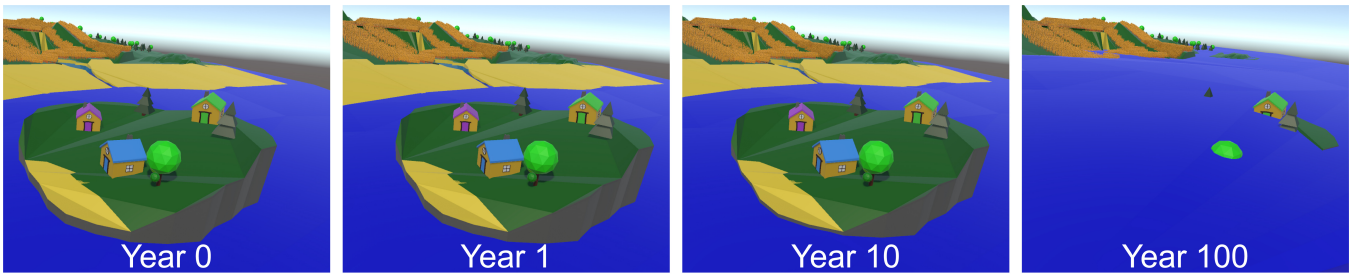
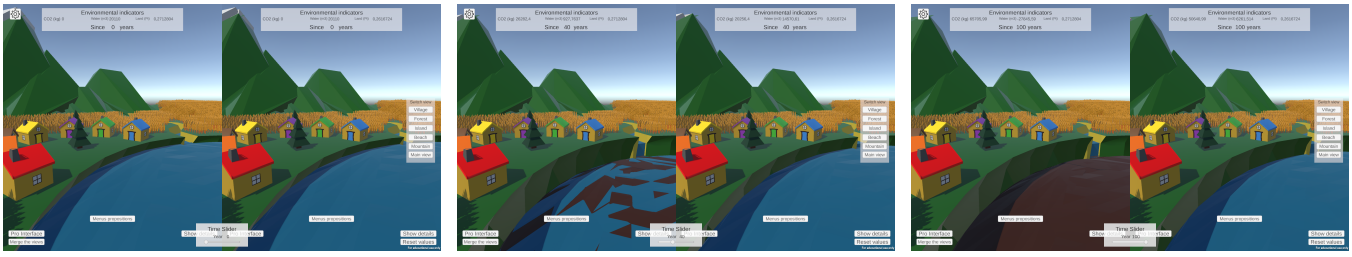


Figure 3: Exploranation of GHG emissions which are twice as high as what the mini-world's carbon sinks can absorb. From one year to the next, changes are barely noticeable, but they do add up over time: The island starts to be threatened after 10 years, and it is flooded completely after 100 years.

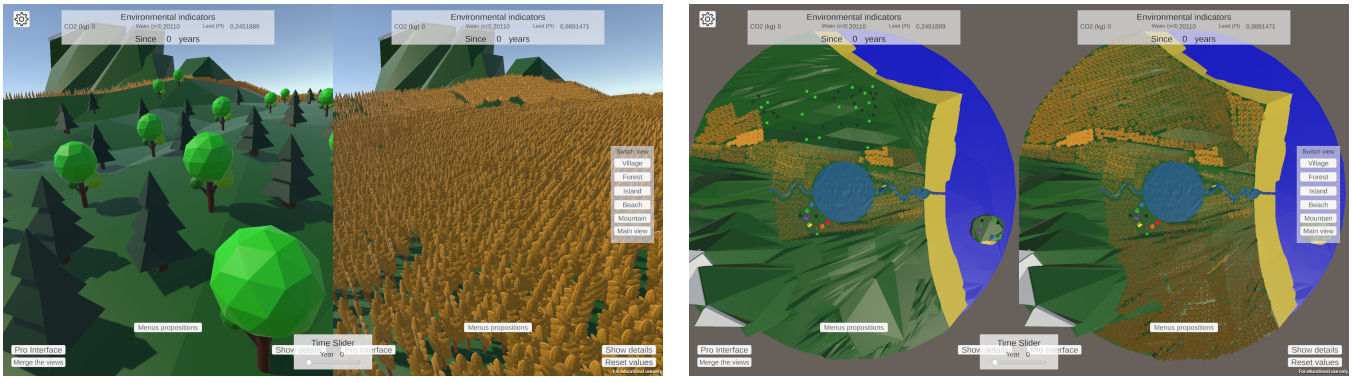


(a) At year 0 both worlds look the same.

(b) After 40 years, the "chicken diet world" is running out of freshwater.

(c) After 100 years, freshwater is going down in the "all protein but beef world" (it is not sustainable), but it has not yet run out of water.

Figure 4: Exploranation of freshwater use comparing a "100% chicken" diet (shown on the respective left panels) against an "all proteins but beef" diet (the respective right panels).



(a) Forest view

(b) Top-down view

Figure 5: Exploranation of the land use indicator comparing "100% fish" (left panels) with "100% beef" (right panels).

that the carbon sinks (forests and ocean) are already saturated, that is, a total of 1.2 tons were emitted, of which the carbon sinks captured 0.6 tons, and the additional 0.6 tons go straight into the atmosphere. This corresponds to what happened during the last years on Earth: we emitted double of what our available carbon sinks can absorb. This scenario can be reproduced in the mini-world with the "100% chicken" menu. Figure 3 shows screenshots taken from the timeline of such a scenario. Emitting 0.6 tons of GHG each year in the atmosphere leads to a small, invisible increase of the sea level every year (cf. year 0 and year 1). Ten years later, the increase of the sea level becomes noticeable (cf. year 1 and year 10), and 100 years later, the island is almost completely flooded (see year 100).

The projected sea-level rise in this exploranation is not an accurate model of what will happen on Earth. Instead the message it aims to communicate is that even if we cannot see small changes from one year to the next, these still sum up and can have large consequences over time.

3.6.2 Comparing water use for different diets. The mini-world simulates water scarcity as described in section 3.4, and this can be best observed using the village view. Figure 4 shows the development of freshwater availability for years 0, 40 and 100. Each side shows the mini-world assuming a different diet: on the left a "100% chicken" diet, i.e. eating chicken at every meal, and the "all proteins but beef" diet, i.e. eating evenly all proteins, except beef. At year 0, the two versions of the mini-world look the same (Figure 4a). At year 40 the "chicken world" used up most of the water, and the lake is almost empty (Figure 4b). After 100 years, the lake in the "chicken world" is completely dry whereas in the "all proteins but beef" world, water remains in the lake, albeit at a visibly lower level than at year 0 (Figure 4c).

3.6.3 Comparing land use. The forest and top-down view are the most suitable viewing angles to explore land use. Figures 5a and 5b illustrate differences between a "100% fish" diet and a "100% beef" diet: on the respective left sides, the mini-world is covered in a mix of forests, pastures, and agricultural land. This is because a diet using fish as protein source has a relatively low land use impact. On the other side of the spectrum, a diet based mostly on proteins coming from beef, shown on the respective right panels, transforms all arable land into wheat fields required to feed the cows. Note that one of the simplifications made in the implementation of the system is that the encoding of land use does not evolve over time. This is because (1) the mini-world does not model changes in population and (2) diet composition is assumed to not evolve over time.

4 INTERVIEWS WITH EXPERTS

We chose to evaluate our prototype by interviewing three experts with different expertise, as suggested by Jordan [35, pp. 172f.], *"because his or her expert knowledge should give the investigator an idea of which the really important issues are in a particular context"*.

We chose this approach because (1) the prototype is not mature enough to be tested with final users who risk getting hung up on usability issues while missing potential conceptual issues, and (2) experts can give feedback to improve the prototype and provide insights to inform future work beyond this particular prototype.

4.1 Participants

We recruited three experts for the interviews. The first expert (E1) holds a PhD in sociology, more precisely in Information Science and Communication. In her research she explores how knowledge of experts and non-experts can be gathered and transmitted. The second expert (E2) is head of the communication and scientific outreach department of a research institute where she manages various scientific outreach events. She previously worked with the French Ministry of National Education where her job was to develop techniques to train teachers, parents and students to the use of new technologies for learning. The third and last expert (E3) holds a PhD in predictive modelling and works on climate change mitigation strategies. He uses models to develop scenarios and explores the potential economic and social risks of possible transition pathways.

4.2 Procedure

All interviews were conducted in French. E1 and E2 were interviewed face to face while E3 was interviewed through a video-conferencing tool. The prototype was tested on the interviewer's computer and via remote control software for the remote expert. Each interview was structured as the following:

- **Step 1.** The expert is welcomed and the interviewer presents briefly himself, his research team and his research interests.
- **Step 2.** The interviewer gives a demo of the prototype, showing its main functionalities.
- **Step 3.** The expert has five minutes to test the prototype freely.
- **Step 4.** A semi-structured interview is conducted by the interviewer to gather insights about the prototype.

The questions asked during the semi-structured interview are structured around two main topics: the prototype content and potential usage scenarios. Questions asked during the interview are available in Table 2.

A. Prototype content
A.1 What are your first impressions?
A.2 What are the elements that appealed to you the most?
A.3 Which part could be useful for scientific outreach? Which part could bother you?
A.4 What do you think of the mapping of the data? Does the visualization convey relevant data?
B. Usage scenarios
B.1 In which situations do you imagine this prototype being used?
B.2 Do you think this prototype could be explored by several users at the same time?
B.3 Does this prototype seems engaging to you?
B.4 What could non-experts withdraw from using this prototype?

Table 2: Common thread of the semi-structured interviews (translated from French)

Since we decided to use semi-structured interviews, each session was slightly different, with each expert tinging the discussion with their own professional viewpoints. Questions were used when the discussion ran out of ideas in order to trigger new insights.

4.3 Analysis methodology

In order to analyze the data, we performed a thematic analysis using Braun and Clarke's methodology [8]. First, we familiarized ourselves with the data by performing a transcription from spoken to written French. Then, we generated codes for each sentence of the interviews. During the next step, we gathered codes under more general themes. Then, we refactored our themes and codes to get three final themes: (1) knowledge transmission, (2) engagement and (3) usage scenarios.

4.4 Results

In this section, all quotations have been translated from French to English by the first author.

4.4.1 Potential for knowledge transmission. Even if we cannot assess the concrete impact in knowledge transmission since we did not test our prototype with end users, the feedback we get from the experts give us insights to assess its overall potential.

Adopting a holistic approach of environmental impacts. Including three planetary limits was appreciated: "*I liked the fact that the impact on land use and water was also shown, so that there was a more global vision than just GHG emissions*" (E3). This is well supported by the different views available: "*Here you have everything, you have the whole cycle. You've got the mountains, you've got the sea, you've got fresh water, you've got all the resources* (E2), "*when I said it was complete, I think the five views, plus the global view, are relevant*" (E3). The views allow users to explore in depth some details of the mini-world representation, exploring the different mappings chosen. The proxy mappings were overall appreciated: "*we can see the repercussions of what you've been eating on various elements*" (E2), "*But otherwise I like the design, I think it's quite complete, as I said*" (E3), "*I find it useful for a quick overview*" (E3).

Explaining the underlying mechanisms. However, in its current state, our prototype has important limitations. Most notably, the prototype only allows a shallow understanding of the concrete mechanisms by which food production harms the environment: "*Since I don't understand what's going on with the water [...] I don't have an explanatory key*" (E1), "*You did say 'The sea is rising' [...] and then the ice is melting, but it's not as obvious as that*" (E1). The experts warned that users may not be able to extract all the knowledge we want to transmit and risk to only understand broad qualitative insights but not quantitative or consequential ones: "*Yeah, [the users would] be a little more aware of the repercussions of [their] choices, that's for sure*" (E2), "*I think [users] would have qualitative information or representations, but I think they would miss out on anything that's more quantifiable, you know? They'd say "Ah, beef [has more impact] than pork", but they wouldn't be able to imagine the quantity aspect, even though it's one of the main interests*" (E3). Our idea to rest on the Naive Physics understanding of lay people may be much too optimistic and links between data and representation should be given more explicitly. Especially when considering people that are not familiar with the exact global phenomena but only have a vague idea of the environmental impacts of food, as E1 does: "*Afterwards, when I put a vegetarian thing [...] it looks like there's no impact at all from being a vegetarian*" (E1), "*First of all, as a vegetarian who eats soy - which, by the way, is a major environmental hazard - my water doesn't move, so I'm not sure what I'm supposed to understand about it*" (E1). Here, E1 expected to have an impact on the mini-world but did not because she had diet habits respectful of her environmental budget. However, she was confused because she knows that soy (among other vegetarian products) also has an environmental impact. More explicit visualizations may be needed to ensure that the underlying principles of carbon sinks and freshwater replenishment are made apparent and not left invisible for a mini-world which is in equilibrium. E1 suggested adding some explanatory windows as optional pop-up in the mini-world to get more information about what is currently happening in order to learn more about the underlying mechanisms: "*I'm always in favour of explanations, but perhaps ones that can be activated. In other words [...] I like it when there's a little "+" you know [...] I click, and it says "Mmmm, there's no more water"*" (E1).

Linking proxy visualizations to numbers. Showing numbers concerning the current state of the system as complementary indicators to the proxy visualizations may be useful to some people but confusing for others to understand the concepts of available budgets or the magnitude of environmental impacts. During our interviews, we saw that the numbers helped E3—who is deeply familiar with orders of magnitude ("*To see that in one of the menus I had 5,000 cubic metres, and 20,000 in the other, I can relate to that*" (E3))—but E1 considered them useless or even confusing at some point: "*The numbers up there. Well, I haven't really looked at them because they don't really mean anything to me. For example, 50,000 [kg of CO_2], I don't know what that represents*" (E1). Since this type of visualization is designed for non-experts, further experimentation should be done to assess if such numbers are useful for those who care but do not imperil understanding for others. Even if E1 and E2 were less at ease with numbers, they advocated keeping them anyway to complete the proxy visualizations. E2 suggested a way to improve the display of the numbers in order to trigger attention and understanding of the users, using gauges turning green, orange or red, as life gauges in video games: "*If it had been more visually appealing to me, I might have been more interested. [...] But I think it's interesting that they're there, though, and you have to leave them there, because even if you can see the effects on the landscape, you also have to see how [the numbers] move according to my choices, with maybe something very simple, like gauges, you know? [...] Just like in video games!*" (E2).

Realistic representations and interactions between limits. A potential threat to understanding is the current choice of mappings of the indicators which can be exaggerated at some point. This is most noticeable in the case of the "100 % beef" menu: "*Yeah, I might have been a little surprised that everything was flooded with beef. [...] I mean, [the ocean] reaches the mountains after 100 years, so it's really huge.*" (E3). With the other diet compositions, the environmental data expert considered the mapping's amplitude quite realistic: "*You see, in terms of the magnitude of the impacts, except perhaps for the rise of the water level [...] I think it's pretty well calibrated because I think we've got quite a large amplitude. It's clearly visible without being too overwhelming. Because if it's too overwhelming, you could get the impression that it's not realistic*" (E3). Here, E3 highlights the importance of having a *realistic* representation. However, the plausibility of the consequences happening to the mini-world has been questioned by E3 in terms of linearity and independence of the impacts: "*Something that bothered me a little*

was that the representation of the phenomena seemed rather linear" (E3), for example "*when you know the dynamics of the coast, there's your water that moves forward, and in fact it doesn't transform the landscape at all*" (E3), or "*if you really did have this rise in water levels, you'd also have a loss of available surface area, and so, you'd also no longer have access to the possibility of eating as much beef*" (E3), and consequently "*it's very strange to have cereals that will continue to grow but there's no more water in the lake*" (E1). A suggestion to cope with this limitation is to use a more complete system model, getting the mini-world functioning closer to the functioning of the Earth, as suggested by E3: "*It bothered me a little because, given that there are possible interactions between the different aspects, it would be an opportunity to show the interactions, and that's something I'd have liked to see, in the end, and which is also something that brings both realism and a little more complexity [...] I have the impression that the representation has the potential to deal with them and doesn't.*" (E3). This systemic aspect has been noticed by E1 too. As she projected herself in the mini-world, she focused on the habitability of the mini-world: "*there are too many things changing that don't seem to have any impact on habitation*" (E1). She noticed that the only threat to the village is when it is flooded by the ocean and disappears. But in other scenarios, the village remains intact even after the lake has been dried up for several years: "*I said to myself, "Whatever happens to the village, even when everything empties out, it's still the same. But in real life, if there's no more water in the lake [...] there are no more inhabitants. [...] So, in fact, there's no house left."* (E1). Thus in addition to showing the interaction between different environmental impacts, the mini-world could also make them explicit on its habitability. Not having clear consequences on habitability could suggest wrong ideas, as maladaptation, like when E1 ironically stated that people should just eat more fish if the ocean floods the lake: "*I mean, in one I saw, the lake fills with salt water. And now I want to say "Bah, okay, you've got to eat fish"*." (E1).

4.4.2 Engagement. Engagement is an important challenge in the context of scientific outreach, because to be able to transmit knowledge, someone needs to want to interact with the mediation tool.

Relatable menus. It appears that engagement with this prototype goes first through a personal projection in the mini-world. This personal engagement translates into the user's agency to choose dietary composition that matches their habits. E1 strongly criticized the basic meals proposed by the prototype based on the same protein 100% of the time, calling them "*caricatured*". She insisted on the need to have realistic meals to have people convinced and engaged: "*to realize how my consumption affects the environment, you have to be in the reality of things. And that's why I say that no one is into basic menus. I don't really know anyone who is. [...] That wouldn't be likely.*" (E1). However, she saw a strong potential in the possibility to compose her own menus based on the week elapsed: "*And in fact, I'm thinking that [personalized menus are] more interesting than caricatured menus.*" (E1), "*The interesting thing is to ask people, "What do you eat? [...] And then, depending on what you eat, what happens?"*" (E1). E2 also agreed on the usefulness of such an approach, arguing that such ways to compose meals are already part of our daily lives: "*Meal planning will speak more to people, because in everyday life, sometimes you do your planning [...], or when you go to college or high school, you have your meal plan posted*" (E2). However, E3 had a different approach and he used the "100%" menus to compare global impacts: "*I found it interesting to be able to test a little bit of everything, and to test extreme scenarios with 100% of one or 100% of the other*" (E3). But he also agreed that these automatic meals could be a threat to engagement since users may not recognize their habits in it: "*Finally, you test, you're a bit of an outsider if you can say "Oh yeah, well, I'm testing this menu, which is the menu of I don't know who[...]", so you're a bit [...] less involved*" (E3). E2 also criticized the input menu with percentages, considering it too conceptual and non-intuitive, especially for non-expert people: "*when you showed me the two ways of making the menu, I thought to myself, for children to say "I'm eating 20% beef" is completely far from being intuitive. [...] And even for adults.*" (E2).

Projecting oneself in the future. Personal engagement also appeared to go through time navigation. The possibility for the experts to project themselves in a future year allows them to explore different environmental consequences as they want to. While E1 chose to explore the 100 years available in the system, E2 chose to focus on year 25. She analyzed her choice through the lens of her own lifetime: "*maybe there's a "That I'll see" side to it. [...] But 100, I think it's a good scale, you can't go beyond that. And anything less would be too restrictive.*" (E2). One of the advantages of time navigation is its direct influence on environmental consequences. Since water consumption and GHG emissions vary across time, people can witness these changes in the mini-world: "*So you see, for example, the disappearance of the island is really interesting because, in fact, you can see a difference, and you can see an effect.*" (E1). However, it makes the land use indicator less visible since it's a static indicator that does not evolve over time: "*Interviewer: You paid more attention to dynamic things than to static ones. / E1: Exactly.*" (E1), "*The forest. I can't quite visualize the changes to the forest.*" (E2), "*The forest, I asked you at one point, "Oh dear, it doesn't move.*" (E2). E3 had an opinion slightly different and thought that the immediacy of the change could be less impactful for users: "*the fact that it was reversible made me less immersed*" (E3). E3 suggests developing a scenario where users are invited to choose a menu and then witness its impact 10 years later before repeating the process. The goal would be to trigger a feeling of irreversibility coupled with an animation taking the time to display the change one year after another. With such improvement, E3 hopes to anchor the experience in the memory of the users: "*If it's reversible, if it's not part of a process [...] you'll have forgotten it a few days later, whereas if it's not, it may be a little more ingrained in your memory*" (E3). This suggestion echoes the one from E1 which found a lack of storytelling in the prototype: "*I'm missing something, a narrative thread, you know? [...] A little one, an islander who talks to me, and says "Now that stinks, it's a good thing we eat vegetarian"*" (E1). In order to increase engagement and immersion, E2 suggests adding gamification elements. For her, simply choosing a menu is not engaging enough, and she would like to be able to directly manage the resources of the mini-world as players can do in resource management games: "*So it's visualization, I see, but, on the other hand, I don't really act. Apart from choosing menus, which is still a very conceptual thing, but in the end, you'd have me pose little pigs, little cows, you see I'd have more of a "I've made a choice" side. I'd be more committed to putting down my little pig and saying "Well, I've decided to eat 50% pork", that's all*" (E2).

4.4.3 Usage scenarios. When talking about potential usage scenarios of such type of visualization, all experts proposed several ideas. The first goal the visualization aims to achieve is to have people realize what the impact of food on the environment is. The three experts agreed that the mini-world had a great potential for raising awareness in lay people, especially by using the split screen functionality. The possibility to compare dietary composition with a split screen was appreciated by the three experts: "*And then you showed me the Split the view, which I think is really cool, so I think it's a really great thing*" (E1), "*The fact that I can compare, even if I haven't used it, is a good thing*" (E2), "*On the positive side, it's true that comparison is very useful*" (E3). E1 suggested inviting people to use the first screen to simulate their current diet habits and the second screen to try a more ecological dietary composition that they could adopt: "*But I could really see this thing, like, "My usual menu" and "What can I change". And what [...] I change completely changes the world.*" (E1). E1 built on her idea and proposed a two-user activity where two people can compare their meals on each screen. E2 had the same idea, but with gamification notions as a "*battle*" whose winner would be the more respectful of the environment: "*the battle aspect, where everyone has their own map and then you have the two of them making choices.*" (E2). For bigger groups, E2 suggested a form of quiz where two people input their diet habits and then a presenter could question participants about what type of meals were chosen based on the environmental consequences they witness: "*Or afterwards, there are two people who make different choices, and the people around them also have to try to guess which choices have been made*" (E2). E3 built on his proposition we described in section 4.4.2 and suggest giving a prototype to each person in a small group and developing a narrative where everyone chooses a meal every 10 years and witness the changes on their world, allowing them to compare with each other: "*each of the individuals in the small group could have their own island where they would have noted what they ate and what was happening. In fact, they could compare themselves with each other, but in any case I'd keep the process to a minimum of 10-20 minutes*" (E3). These usage scenarios with users interacting with each other could have a positive impact on the subjective norms of the theory of planned behaviour, inducing an increase of sustainable intentions and behaviours [1].

Experts also suggested different places where they imagine this prototype being used, with different target audiences. E1 imagined a private setup with her daughter and family members: "*with my daughter, for example, or with all the people in my family*" (E1). The system could be included in events like science exhibitions: "*I could see it in an exhibition, I don't know, on global warming, rising sea levels, stuff like that.*" (E1). E1's ideas are in accordance with those of E3 who suggests using such a system in a supervised activity: "*It could also be an exhibition, you know, where you have the first panels to read and then, you start by filling in what you've eaten, you have the other panels to read, you see the impacts in 10 years [and so on]*" (E3). E2 suggests two additional ideas. The first one is to use this system as an educational tool for science teachers in high schools in order to raise student motivation ("*With little serious games like that, maybe you can re-motivate a class. Maybe teachers could find it interesting.*" (E2) or to assist elected officials to help their population understand the reasoning for laws to be adopted ("*a mayor who wants to make decisions like that, well, sometimes he first has to raise awareness, and reassure people that this decision isn't being made because he suddenly wants to put green everywhere, but because for your fellow citizens, there will be real repercussions, fairly quickly in fact, 25 years down the line.*" (E2). Finally, E3 suggests using this kind of system to raise awareness of elected representative and stakeholders: "*And afterwards, it can also be used with decision-makers, for example.*" (E3).

5 DISCUSSION AND LIMITATIONS

Instead of using classical visualizations with charts, we took advantage of the concrete context of the data to design proxy visualizations building a bridge between the data and its meaning within the real world. We developed a mini-world to explore how this approach could be used to communicate environmental data related to food consumption, and asked three experts for their insights concerning the perceived potential of such an approach.

5.1 Challenges when visualizing complex environmental data

5.1.1 Risks of simplifications. Actual models used by experts of climate change mitigation strategies such as E3 contains more than a thousand parameters and model the interplay between all of these [37]. To design the presented mini-world, we created our own very simple linear model, based on the principles of how the Earth functions, yet dramatically simplifying the complexity of research conducted by environmental scientists. Our goal was not to give a perfect description of a likely reality. We only aimed for a global comprehension of different environmental impacts of food suitable for a non-expert, in a simple and engaging way. Consequently, the speed of glacier melting and sea level rising may be disproportionate in some cases and the actual consequences of eating beef every day may be different from what our mini-world shows. Nonetheless, as E3 summarized it, the prototype allows to get an overview of three planetary boundaries by proposing quantitative ideas. By exploring GHG emissions, freshwater consumption and land use, we wanted to explore more than climate change (GHG emissions), which is a pervasive topic in the SHCI literature (e.g. [33, 38, 39, 50, 58]).

However, we may have simplified the model too much: E3 specifically regretted the lack of interaction between the different indicators. Indeed, since the visualization is a mini-world, he expected to notice an interconnection between environmental impacts that we did not implement. Because of the linearity and the independence of the included indicators, the mini-world evolution is not what will happen in the future. While we never intended to suggest this, people interacting with the mini-world may easily understand it that way, because it is anchored in an environment inspired by reality. This in turn could result in a backfire effect [43] or in a complete misunderstanding of the dataset. There is always a tension between giving a simplified intuition of a complex process—such as the impact of food production on the environment—and remaining true to the data. Simplification could also be interpreted as an intent to mislead people, but they are necessary to make scientific research accessible to broader audiences. One solution could be complete transparency about the functioning and assumptions underlying the mini-world. More research will be needed into how to strike

a good balance between simplifications and maintaining accuracy, and how to best be transparent about the choices and assumptions that were made.

5.1.2 Visualizing aggregated scores. Many environmental indicators are aggregated scores, such as the Product Environmental Footprint (PEF) score [19] or the land use impact. These are dimensionless quantities which facilitate their integration in computational models and can provide a single indicator to capture processes in a complex domain. It is straightforward to encode such scores, for example, as bars in bar charts. Visualizing them using more concrete representations is however challenging. It then requires to either interpret the score's meaning and to link it to the spirit of the scores, or to try to decipher the aggregation to find the initial impact values which can be used as representations.

For this prototype, we initially tried to decipher the aggregated score of land use to extract the surface of land required for different diets. Since the land use indicator includes a quality index and the surface used, we decided to represent it by an expansion of agriculture fields (adding wheat fields represents an increase in surface used) and a destruction of natural ecosystems (removing forests represents a loss of biodiversity). However, this choice of representation is reductive, since increasing beef consumption leads indeed to an increase in cereal production for beef feeding, but also in an increase of farms and infrastructure where cows are bred, which is not represented in this visualization. Consequently, using wheat fields to summarize land use is somewhat inaccurate and possibly even too positive, as wheat fields could trigger enjoyable memories of the countryside. Additional storytelling mechanisms will be necessary to communicate more of the complexity around the score, as suggested by E1 and E2.

Overall, visualizing aggregated scores adds complexity to the mapping between data and visual parameters because of the loss of information due to the aggregation and because of the richness of impacts hiding inside such aggregated scores.

5.1.3 Exaggerated feedback. Data representations in the prototype have been designed to give an intuition of the consequences of food consumption on the environment based on simplified linear models. Testing a diet composition respectful of the planetary boundaries leads to generate a representation that remains almost unchanged through the years. However, testing a diet representation which consumes many of the mini-world resources tends to change the representation considerably. For example, the extreme case of eating beef twice a day all year-long would completely flood the mini-world and see the sea level rise to the top of the mountain. Of course, it would not happen like this in the real world. However, even if the concrete outcomes are exaggerated, the overall message is not wrong: eating beef twice a day would have a tremendous impact on GHG emissions, and if all people in the world started doing so, climate change would accelerate considerably.

Such exaggeration could be a problem because of the analogy with the reality. What is rendered in the prototype is not what will happen in reality. Exaggeration was needed to make visible small yearly changes which is what, in the end, enables the viewer to realize whether a diet is sustainable (that is, results in a mini-world in equilibrium) or not. However, the exaggerated feedback, when interpreted literally as a prediction of what might happen in the real world, could also be an accelerator of eco-anxiety. Its use should therefore be clearly communicated to people interacting with such a system.

5.1.4 Representing a sustainable diet. In our prototype, there is only visual feedback for unsustainable diet habits. However, it confused E1, especially in the case of soy consumption. Since every food produced has necessarily an impact on the environment, she expected changes in the visualization. However, since eating plant-based proteins is sustainable, no change is visible in the mini-world.

This example shows that pre-existing knowledge about the environmental impact of food varies between people and some expect meals to have specific consequences. This prototype could be a tool for them to re-evaluate their knowledge. However, this specific case highlights a limitation concerning the visualization of sustainable diets through a mini-world paradigm. Since there is no feedback, it could be interpreted as an error in the prototype. One way to address this limitation could be to add some positive feedback, such as flowers blooming or adding wild animals in the mini-world. In a more neutral way, we could show the total amount of GHG emissions since the beginning of the simulation to complement the number of GHG emissions emitted in the atmosphere. Such an additional feedback mechanism would make it clear that, even if the available carbon sinks are able to absorb all GHG in the case of sustainable meal choices, the total amount keeps increasing nonetheless.

5.2 Limitations of proxy visualizations

5.2.1 Many phenomena are too complex and not well known. When we began to design the prototype, we were interested in all the different indicators available in Agribalyse. Among the 16 environmental indicators used to compute the global PEF score, some are more intuitive than others. For example, the indicator "Ionizing radiation" is not familiar to non-experts, whereas "Water use" is much more concrete.

The guiding principle for this work was to use realistic proxies to encode data in the hope that pre-existing naive knowledge of lay people may facilitate the understanding of the phenomena represented. The expert interviews challenged this hypothesis as they asked for more explanations for the proxy visualizations, suggesting a variety of methods such as optional pop-ups in the software, panels in an exhibition or through a discussion with a presenter. Here lies an important challenge: how can we communicate such environmental mechanisms with clear proxy visualizations and only little additional textual or oral explanations? That challenge grows with other, less known indicators. For example, "Ionizing radiation" is not a well-known concept on which one could build a proxy visualization, and it needs a detailed explanation on its own (it is an indicator corresponding to the effect of radioactivity due to nuclear plants and is measured in kilobecquerels U235 equivalent).

5.2.2 Not all phenomena easily map to visual proxies. Taking again the example of ionizing radiation, it is not obvious how a proxy for such an indicator could look like. How could we represent radioactivity in an intuitive way? Pop culture sometimes uses fluorescence to suggest that something is radioactive. In terms of direct effects on people, high exposition to radioactivity tends

to burn skin and modify the cells and chromosomes, leading to wounds and later often cancers, according to the Radioprotection and Nuclear Safety Institute (IRSN) [32]. However, in a food production context, ionizing emissions are very small and would not create such injuries, because nuclear plants emit very little radioactive particles and are strongly controlled. In this particular case, we can ask ourselves how to represent such an indicator with a proxy visualization that does not rely on detailed labelling and explanations. It seems that the scale of the mini-world is too big to integrate a precise indicator like this one.

5.2.3 Combining individual and systemic effects is challenging. Proxy visualizations have been designed based on individual budgets: a personal carbon sink, a personal water replenishment, and a personal area. However, even if the mini-world is based on an individual's budgets, it can be seen in two ways. Either it is a one-person world designed to provide resources to a unique individual or it is a small world similar to the Earth and the person interacting represents humankind, i.e., as if each meal chosen was eaten by everyone on the Earth, polluting the same way. Yet, it is not clear how to best communicate that the mini-world can be interpreted in these two ways. The phrasing of the instructions in the menu view may play a significant role here, that is, asking people what they ate the last five days is more likely to result in an individual interpretation whereas adjusting different levels of different food groups could be interpreted more as "setting policies". An alternative approach was used by Jach [33] who, in a VR visualization of food impact on the environment using storytelling, multiplied a user's choices by the number of people of the Earth.

5.3 Reflections on the design and the methodology

The current prototype includes a very limited set of food options. While those capture the different orders of magnitude one can encounter for different food types, people interacting with the system would likely feel limited and appreciate more choices. One could also expect that more available food option would be beneficial for the level of engagement achievable with the design. Most importantly though, the prototype would likely gain in expressiveness if the modelling, which determines the behaviour of the mini-world, takes interactions between indicators and effects into account. Additionally, experts suggested to include effects on people, such as loss of habitable space due to a rising sea, or loss of available food due to lack of water. However, taking effects on people into account in a mini-world without explicitly modelling and visualizing people moving around would be challenging. The prototype specifically avoided showing people or even suggesting how many people could be living on the mini-world to enable the dual interpretation of it being the world *of* the person interacting or a world *governed by* the person interacting.

Concerning our choice of evaluation method, that is expert reviews, we believe that our results confirm that this can be a valuable tool in the HCI toolbox. All experts provided insights, guided by their respective expertise, for which we believe that we could not have gained these through an evaluation with naive end users. However, experts need to be chosen carefully to cover different aspects of the important properties one aims to have reviewed. Also, if the aim of the prototype is to prepare it for deployment, then an expert review does not replace an additional usability study to identify potential issues in a user interface.

6 CONCLUSION AND FUTURE WORK

In this paper, we introduced a new kind of data visualization about the environmental impact of food. Based on the vivid origin of the data, we encoded it through proxy visualizations mimicking environmental impacts in a mini-world, such as rising sea levels or melting glaciers. Different diets can be entered and compared to explore consequences over time and compare what kind of diets can result in a mini-world in equilibrium.

We report the results of interviews conducted with three experts in scientific outreach and environmental data. They all recognized the potential of the proxy visualizations to communicate knowledge to non-experts about three planetary boundaries, but they also pointed out clear limitations. Most importantly, the link between the data and its encoding need to be better communicated and additional storytelling or gamification elements could improve user engagement and projection in the mini-world.

The main takeaways of our work are: (1) proxy visualizations have potential to engage and transmit knowledge to non-experts about environmental data, but (2) this kind of visualization may not be self-sufficient to insure a complete understanding of the environmental phenomenon, potentially requiring storytelling or gamification elements or a mediator as guides of the mini-world. There is also, (3) a risk that proxy visualizations distort scientific outcomes due to oversimplifications and in themselves cannot explain the underlying mechanisms of visible effects. Finally, (4) when talking about environmental impacts, it is important to include as many planetary boundaries as possible and to have their environmental consequences interact with each other.

Our work opens several directions for future research. The prototype could be improved based on the insights provided by the experts: (1) including interactions and feedback loops between effects, (2) improving the communication of environmental mechanisms through storytelling elements to engage users and have them better understand the consequences of planetary boundaries, and consequences of exceeding them and (3) adding some gamification aspect to engage more users.

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APPENDIX

The prototype includes three different ways to enter diets.

The *basic view* (Figure 6) only offers the choice between a predefined set of simplified diets. The protein source has the biggest impact among all food types, thus this view focuses only on protein sources.

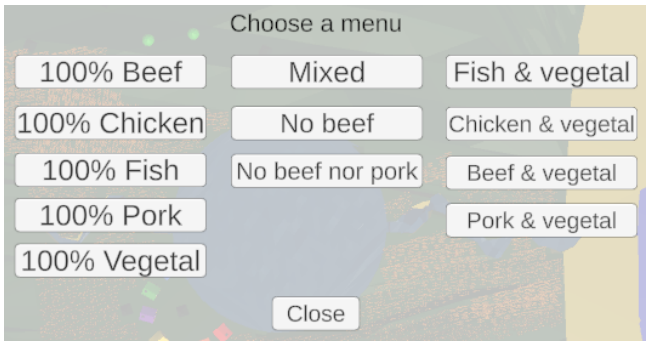

Figure 6: The basic menu view providing a fast but restricted way to compare protein sources.

The *consumption view* (Figure 7) asks for more detailed information on the diet composition in the mini-world. It requires to fill in percentages for different protein sources and additional food types, such as dairy and fruits. This view is useful, for example, to compare custom diets, such as "some meat but no dairy" or "mostly vegetarian".

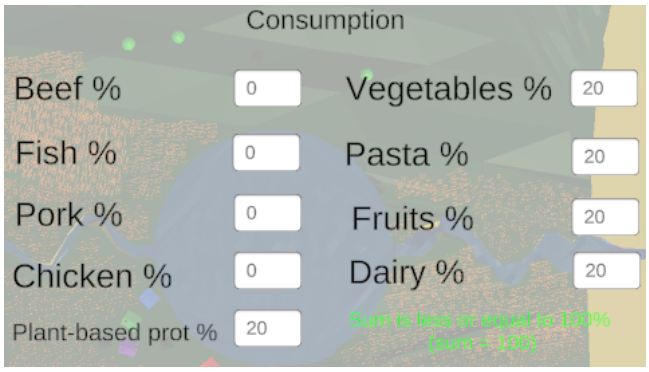

Figure 7: A more detailed interface to consider the consumption of different food types in the form of percentages.

The *past menu view* (Figure 8) asks for one's eating habits over the past five days and, assuming that these short-term habits are representative for one's year-long eating habits, extrapolates from this data a diet. One can enter protein choices for lunches and dinners, and add from which other food groups one consumed.

Figure 8: An even more detailed interface to set food types one consumed for each lunch and dinner over five days.