CO-DESIGNING WITH NATURE: INTEGRATING ENVIRONMENTAL PROFILING AND REMOTE SENSING METHODS IN THE DESIGN PROCESS

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ABSTRACT
Sustainability is becoming a fundamental consideration in engineering and product design, requiring approaches that minimise environmental impact. Environmental profiling and remote sensing offer structured ways of evaluating site-specific biomarkers to support data-driven, non-intrusive design interventions. The aim of this paper is to examine their roles in sustainable design and to propose a structured framework for co-designing with nature. Insights from case studies present the effects of integrating remote sensing into nature-based design, in conjunction with the dissemination of the created environmental profile and captured data through interactive visualisation tools. Implications of applying the suggested workflow in various educational contexts, modes and curricula for fostering sustainability-driven design thinking are also provided, focusing on teaching emerging tools and promoting interdisciplinary student collaboration.

Keywords: Environmental profiling, remote sensing, nature co-design, sustainable design

1 INTRODUCTION
Sustainability has become a critical priority in engineering and product design, as organisations aim to reduce environmental degradation and mitigate the ecological footprint of newly developed products and systems [1]. In cases where design interventions directly interact with natural ecosystems, the need for data-driven environmental assessment methods is even more evident. Traditional environmental guidelines often rely on qualitative judgement and heuristic approaches, lacking systematic integration of real data and scientific assessment [2,3]. However, emerging environmental profiling tools and remote sensing methods offer a structured way to assess and monitor ecological conditions, enabling sustainable and non-intrusive design interventions. Incorporating environmental profiling into design methodologies has significant potential, particularly in projects where human-made interventions in nature are necessary. The adoption of such nature co-design approaches in design education is essential to equip future designers with the knowledge and skillset required to make ecologically responsible decisions in a world where sustainability is increasingly established as one of the primary concerns.
This paper will present two case studies in which environmental profiling and remote sensing for biomonitoring purposes play a crucial role in optimising environmental conditions. Based on produced insights, we propose a sustainable design framework and workflow for *Co-designing with Nature*. We will be discussing how ecological data can assist in the design configuration of product interventions, in the monitoring and evaluation of their natural impact, as well as the role of visualisation tools in the accessible communication of it to ensure informed decision-making. Finally, we will outline how students can adopt the presented methods in similar contexts and discuss the implications of integrating nature co-design approaches in education curricula.

2 REVIEWS OF THE LITERATURE
2.1 Environmental considerations in the context of design
The integration of environmental knowledge in product design processes predominantly occurs via *Design for the Environment* (DfE) guidelines [4]. DfE includes an array of methods focusing on reducing the environmental impact of products, processes and services throughout their entire lifecycle [4,5]. These strategies involve material-selection tools, minimisation of resource consumption, waste management, reuse and recycling among other considerations since the early design stages. Developed

frameworks are aimed at further structuring the integration of DfE principles and categorising them based on process stage, to effectively influence product development from the outset, as proactive decision-making tools [5]. Others have also proposed hierarchical frameworks that emphasise the prioritisation and tailoring of DfE guidelines based on potential impact, over generic considerations, thus encouraging the application of strategic interventions to minimise environmental footprint [6].
Nevertheless, DfE exhibits limitations that hinder its effectiveness in driving truly sustainable product design. Many guidelines are fragmented and incomplete, with a predominant focus on material selection and end-of-life strategies, while the lack of structured methodologies leads to ad hoc or experience-based principles that are difficult to adopt and adapt across different industries and product categories [2,3,5]. Another associated disadvantage is design fixation, where designers become constrained by the provided DfE suggestions in the conceptual stages [4]. Moreover, DfE frequently presents conflicting recommendations, making it difficult for designers to resolve competing environmental objectives without clear prioritisation frameworks [6]. Finally, their heavy reliance on Life Cycle Assessment (LCA) as a retrospective tool further reduces their effectiveness, due to its attention on later phases of embodiment, production and recycling [3,7].

2.2 Environmental profiling, baselining and digital tools

Examples of data-driven methods which enable the efficient tackling of nature monitoring issues include *environmental profiling* and *environmental baselining*. These two concepts belong into the broader spectrum of environmental analysis, and they provide structured approaches for systematically gathering and interpreting environmental data and biological components in relation to biotic (living) and abiotic (non-living) parameters such as animal species, humans or vegetation and climate, soil ingredients, topography and carbon emissions respectively [8]. *Environmental Baselining* usually concerns a preliminary, project-specific type of assessment aimed at capturing the current environmental situation against which future progress can be measured and compared, before any interventions are introduced [9]. In this way, they establish pre-development conditions and serve as a benchmark for future environmental monitoring, which is valuable in large-scale projects such as waste management or infrastructure development, where ecological changes must be monitored [10]. Conversely, *Environmental Profiling* refers to establishing an inventory of features, characteristics and activities along with their impacts to the environment [11], but most importantly, their changing patterns over time. This also involves systematically analysing spatial and ecological variables, often using advanced digital, geospatial tools such as Geographic Information Systems (GIS) and remote sensing [12]. Recent advancements have introduced further computational approaches to environmental analysis, integrating data-driven models such as back-propagation algorithms and analytic hierarchy processes to improve accuracy and predictive capabilities [13]. Such emerging methodologies enable the assessment of environmental risks in a quantitative manner, in cases of optimising land-use planning, or informing conservation strategies. Still, the increasing complexity of environmental assessments has also raised the need for simplification strategies to ensure that evaluation processes remain both effective and practical for decision-makers and designers [14].

2.3 Need for a novel, environmentally responsive design approach

In the context of design, one of the key faced challenges lies in the poor quantification of environmental impacts, as many DfE guidelines remain qualitative and heuristic-based, limiting their applicability in data-driven decision-making [3]. Relevant research highlighted that, although quantitative methods such as LCA provide measurable impact assessments, they require extensive datasets which are not available in early stages; in contrast, qualitative methods i.e. guidelines or checklists, may be more intuitive and accessible but lack detailed impact quantification [7]. Most importantly, while DfE approaches provide significant value in reducing ecological footprints, they do not thoroughly consider the design of human-made interventions that directly interact with the environment, such as ecological restoration systems, agricultural equipment, land protection structures, as well as the design of farming processes. Therefore, there is a need for a new approach where designers co-design with the environment and dynamically elicit and fulfil its requirements, to not only minimise harm, but dynamically contribute to its stability and resilience. Processes such as environmental profiling and baselining may facilitate this by providing the means to comprehend and continuously monitor ecosystems before and after human interventions. Thus, the structured integration of conventional field-based assessments with the presented digital tools is crucial to inform novel nature co-design approaches through the establishment environmental profiling and baselining as essential methods in nature management and sustainable design.

3 APPLYING NATURE ASSESSMENT AND MONITORING IN DESIGN

Two case studies conducted by the authors illustrate how profiling, benchmarking and remote sensing methods are employed to support data-driven, sustainable design decisions for product interventions that directly interact with natural ecosystems. Adopting approaches that prioritise environmental considerations, the studies explain how either static structures (coastal installations) or dynamic systems (autonomous mowers) can be designed to minimise ecological disruption and actively contribute to ecosystem restoration through real-time monitoring and adaptive decision-making (Figure 1).

The **1st** case study investigated coastal defence structures, leading to the development of a digital visualisation system designed to monitor the effectiveness of these installations and communicate their potential environmental impact. The project involved designing the architecture of a waterproof and sustainable IoT setup for fitting on the installations, which required certain design modifications to efficiently integrate the sensor modules. Data collected from the sensors was transmitted via cloud technology to Augmented Reality (AR) applications, showcasing the dual functionality of the installations - promoting saltmarsh regeneration through revegetation and protecting the coast from erosion – while also displaying relevant biometrics of the area. The interactive nature of developed tool promotes higher levels of stakeholder engagement and data-driven environmental decision-making.

The **2nd**, ongoing, research project aims to promote a sustainable tea-growing process, via the deployment of an autonomous electric mower. This includes its design customisation for monitoring and responding to the identified environmental data through smart sensing equipment, contributing to the optimisation of the plantation and the living health of the site. Environmental factors include the topography of the site and the mowing layout of the plantation, along with key ecological biomarkers such as soil composition, plant growth/health and climate conditions. Monitoring of data will be performed through the development of a Digital Twin (DT) of the site and an interactive visualisation interface which will also facilitate the control of the mower and its sensing modules.

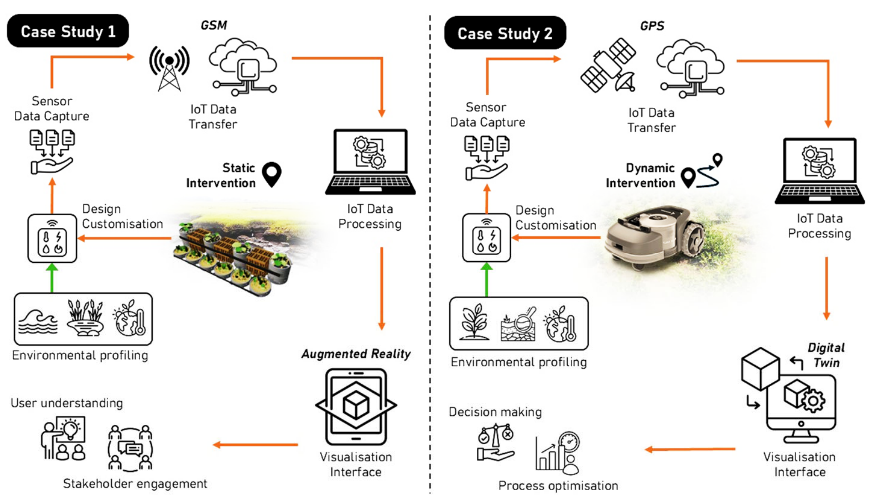

Figure 1. Data flow and methods used: Static intervention (left) and dynamic intervention (right)

3.1 Discussion: Establishing commonalities & Framework Development

Both studies highlight the importance of understanding the site's **environmental profile** as a foundational step, i.e. the analysis and mapping of datasets on topography and elevation data, climate, sediment and soil composition along with biodiversity factors to provide a holistic understanding of the area and rationalise the need for intervention. This is followed by capturing data on existing conditions, before any intervention, which serves as a reference point for monitoring and benchmarking in later stages. **Remote sensing** is integrated as a means to continuously monitor environmental conditions, ensuring that design interventions are adaptive and responsive. Once the key environmental metrics are established, IoT smart sensors are deployed in both cases to capture real-time data. In the saltmarsh project, sensors monitor sediment composition, tidal pressure and absorbed wave force, whereas in the tea-growing project they track soil and plant health, climate conditions and mowing parameters. To ensure that sensors and monitoring systems are seamlessly integrated without affecting the core functionality of the interventions, **design customisation** tasks are apparent in both static and dynamic interventions. For saltmarsh restoration, waterproof sensor modules are strategically placed according to the type of data they capture, in accordance with the installations' structural design. Similarly, the autonomous mower is modified to accommodate additional sensors while preserving its primary role via efficient mowing patterns. Finally, a key similarity lies in the communication and **visualisation** of the environmental data, including both the developed profile and the captured benchmarking metrics. The adoption of emerging technologies such as Augmented Reality and Digital Twin enables the depiction of data in a more accessible and interactive manner, enabling contextual understanding and efficient decision-making. This has also been achieved via the usage of 3D scanning and 3D modelling tools for anchoring data to realistic representations of the sites in both cases.

Commonalities in the followed workflows and adopted methods form the foundations for envisaging a generalised framework, aimed at nature intervention design. Its systematic workflow (Figure 2) demonstrates how environmental profiling, in conjunction with remote sensing and interactive visualisation can guide adaptive, site-specific interventions for nature-based projects via design decisions which are informed by ecological feedback. The suggested **Co-Designing with Nature** approach enables continuous environmental monitoring through remote sensing and benchmarking results against the environmental profiles. In this way, interventions are responsive and ecologically adaptive, aligning design practice with ecosystem resilience.

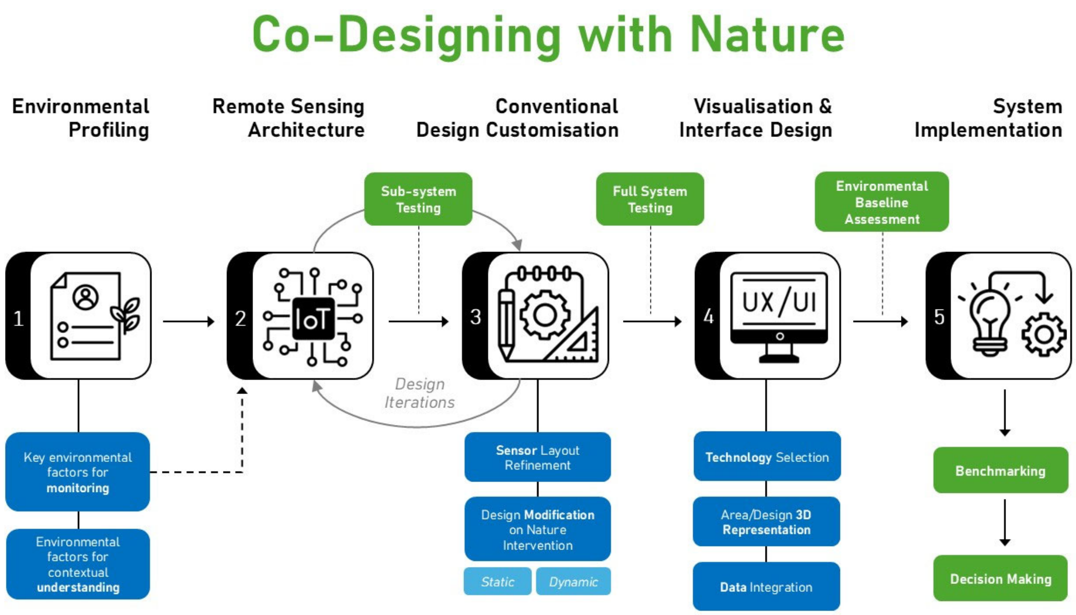

Figure 2. "Co-Designing with Nature" framework and suggested design workflow

4 POTENTIALS OF "CO-DESIGNING WITH NATURE" IN EDUCATION

The integration of sustainable design approaches in teaching faces several challenges, mainly related to limited awareness of environmental issues and resource constraints. Traditional curricula often lack early-stage integration of holistic thinking when it comes to environmental design; consequently, failing to address complex challenges [15]. Additional challenges include barriers in accessing real-world environmental data which negatively impact experiential learning methods and lack of interdisciplinary collaborations [15]. Besides, most recommendations for teaching sustainable design often focus on DfE principles, i.e. design-for-recyclability, circular economy, and LCA tools [5,6]. From the authors' own teaching experience, the lack of design methodologies tailored to nature-based interventions also leads students to conventional guidelines, which fail to address ecological integration and responsive design. The proposed nature co-design approach shows significant potential in tackling these issues. Related research has already provided key insights which align with nature-based design, including the need for Whole-Systems Thinking from early stages to prevent unintended consequences, the shift from exploitative to regenerative design, the importance of evidence-based environmental impact assessments, and ensuring design choices are guided by quantifiable environmental data [1]. Most importantly, comparable Design Thinking-based approaches have been used to reinforce students' sustainability awareness, by engaging them in real-world problem-solving tasks where they examine environmental, societal, and commercial challenges linked to a fragile wetland ecosystem [16]. This shows that design-driven, collaborative approaches hold great potential for environmental issues due to their empathic nature, requiring designers to listen to, understand, respond and adapt to ecosystems, *much like they would in human-centred design, by putting nature at the forefront of the process.*

4.1 Environmental profiling and visualisation tools in the design process

Embedding environmental profiling and benchmarking as research methods in design processes may offer multiple benefits to students with respect to developing more focused problem definitions and eliciting detailed product requirements via analysing existing environmental data. In this way, they can thoroughly explore and understand the solution space before moving onto concept generation. Moreover, the introduction of geospatial tools (GIS), which are not commonly taught as part of design courses, can assist students in considering alternative ways of disseminating their research outputs in a more appealing manner, leading to valuable feedback and user engagement. Yet, it is essential to teach student designers how such tools can be used alongside existing visualisation methods and emerging technologies such as Virtual/Augmented Reality, Generative Design and Digital Twins. Digital mapping and geospatial tools can be integrated within the same workflow for the creation of seamless, interactive user experiences, merging ecological data with design representations. The development of user-friendly and intuitive UI/UX interfaces ensures that outputs are accessible and easily interpretable for non-technical audiences, as shown in Figure 3. The introduction of advanced tools can benefit students by enhancing their 3D modelling expertise across various software platforms during CAD-based courses, enable them to develop novel skillsets, and engage in innovative ways of prototyping, evaluating and refining their designs through nature-based simulations. Digital technologies play an increasingly crucial role in monitoring and mitigating environmental impact, thus design education must prepare students for both industrial and academic future roles.

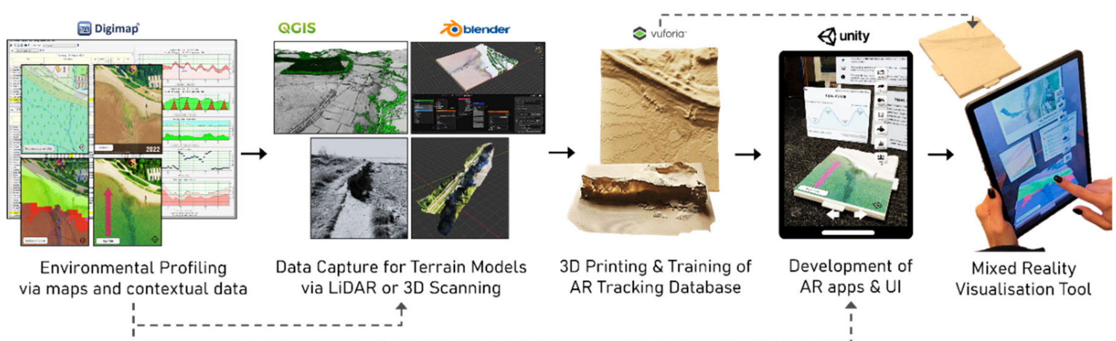

Figure 3. Integration of mapping/GIS tools with 3D modelling, 3D printing and UI design workflows

4.2 Interdisciplinary student collaboration

IoT technologies and remote sensing already form a core part of education in mechatronics and automation university courses. Nevertheless, the 5 stages of our proposed framework show how it can foster interdisciplinary collaboration when applied to project-based learning contexts. While students with the aforementioned skillset can bring expertise in aspects of sensor calibration and configuration, automated control, coding and data incorporation, design-oriented students can focus on conventional design modification and refinement, and visualisation or UI design, while also developing a basic knowledge in remote sensing principles and hardware-software compatibility.

Encouraging such interdisciplinary and cross-disciplinary collaboration in education mimics real-world, professional practices and better prepares students for industry roles where sustainability-led design requires teamwork and diverse expertise. Case Study 1 has already demonstrated the effectiveness of this approach by involving a team of postgraduate students taking part in two courses, Mechatronics & Automation and Product Design Engineering, who contributed their knowledge to explicit project areas. Given the growing emphasis on sustainability in design education, there is significant potential for further employing the suggested nature co-design framework across student-led projects. Expanding design curricula to integrate collaborative, cross-disciplinary experiences is crucial for enhancing students' practical learning, allowing them to engage with realistic challenges and systematically encompass sustainability components in their design and problem-solving work.

5 CONCLUSIONS

This paper has explored the role of environmental profiling, remote sensing and interactive visualisation methods in facilitating the data-driven, adaptive design interventions which go beyond the conventional DfE guidelines taught in design courses. Through two case studies, a structured framework and proposed design workflow were developed addressing the need for early-stage impact quantification and continuous ecological monitoring. The potential application of *co-designing with nature* approach in education can provide benefits in interdisciplinary learning, industry-student collaboration, and experiential problem-solving, during sustainability-driven projects. As digital technologies increasingly shape environmental management and sustainable design, embedding novel principles in academic curricula will prepare students for future professional and research careers where adaptive, ecosystem-responsive design solutions will be essential in tackling global challenges.

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