Developing an Ecology-Integrated Gaming Tool for Collaborative Landscape Design

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Abstract: Long-term success in landscape planning and ecosystem restoration relies on continuous engagement, exploring alternatives, and collaborative creation and design to develop sustainable spaces. However, stakeholders often struggle to contribute effectively due to limited ecological knowledge and planning experience, making it difficult to select strategies and anticipate outcomes. Leveraging video game engine technologies that integrate environmental data, models, planning rules, and interactive 3D visualizations, this study introduces an ecology-integrated gaming tool. The tool automates the generation of landscape elements, including local vegetation communities, and allows users to explore and combine land-use and restoration strategies for given areas. This paper outlines the tool's development workflow, including modeling and visualizing current landscapes, developing Procedural Content Generation (PCG) graphs for automated generation, and integrating generated content with Graphical User Interface for interactive co-design. It concludes by highlighting the tool's potential to enhance collaborative landscape design and participatory restoration while discussing future prospects.

Keywords: Co-design, vegetation community, procedural content generation (PCG), participation, ecosystem restoration

1 Introduction

Active stakeholder engagement is a precondition for successful ecosystem restoration in landscape planning, benefiting both nature and human well-being (PALMER & STEWART 2020, LÖFQVIST et al. 2023). Collaboration among stakeholders with diverse knowledge, experiences, and perspectives is essential for achieving a shared vision on alternative futures, fostering sustainable ecosystem restoration and landscape inclusiveness. In addition to decision-making based on verbal communications on predetermined scenarios, collaborative design (co-design) promotes active engagement across various design stages, ensuring that designs correspond with community needs, preferences, and values, thus creating more functional, inclusive, and meaningful settings (MANZINI 2015, GAETE CRUZ et al. 2023). Co-design tools include GIS-based tools for site selection such as for housing development (BOROUSHAKI & MALCZEWSKI 2010), or augmented reality applications, e. g. capturing hand-drawn sketches on a base map indicating land use change and then displaying corresponding dynamic simulated flood risk maps (TOMKINS & LANGE 2023). Both examples integrate multi-criteria to better inform decision-making. Alongside economic and ecological factors, landscape perception significantly shapes people's preferences on landscape (KAPLAN & KAPLAN 1989). Implementing co-design in a more immersive way to envision and experience future landscapes, – such as through 3D visualization – is expected to enhance

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decision-making by complementing rational multi-criteria analysis with intuitive perception, achieving a balanced integration of logic and sensibility.

A key challenge in co-designing immersive 3D landscapes is ensuring meaningful stakeholder participation, as individuals lacking knowledge in ecology and planning regulations may find it difficult to identify appropriate areas for proper restoration or landscape management strategies. A lack of knowledge regarding local flora could hinder users in selecting suitable plant species and community compositions that align with the local site conditions and their aesthetic preferences.

Recent advancements in video game engine technologies potentially provide solutions to these challenges by allowing to integrate environmental data and models, planning rules, participatory experiences, and real-time visualizations. These technologies enable immersive visualization of alternative scenarios and real-time decision impact assessment. The resulting tools foster a new paradigm for public communication and collaborative decision-making in environmental planning (BISHOP 2011).

Procedural Content Generation (PCG) frameworks further enhance game engine technologies by automating the creation of complex ecological elements based on local environmental parameters (TOGELIUS et al. 2011). "Procedural" means that content – such as land cover, vegetation composition, or habitat patterns – are generated dynamically by a computer program based on input conditions, rather than being manually created by a designer or developer (SHAKER, TOGELIUS & NELSON 2016). For example, rather than manually positioning each vegetation type within a landscape, PCG algorithms can autonomously allocate plant species to locations based on spatial density and ecological principles (OLIVEIRA et al. 2022). Ecology-focused PCG tools like Unity3D's Biome Generation Tool (SEPÚLVEDA et al. 2023) and Gaia (GOODRICH et al. 2024), and Unreal Engine's (UE's) PCG Biome Core (EPIC GAMES 2024), assist game designers in creating diverse ecosystems by automating the generation of terrain features, vegetation, and other natural elements based on predefined rules and parameter. Using a PCG framework that controls element distribution randomness through proportional weights, vegetation communities can be dynamically generated based on community structure, flora density, and species proportions, aligning with the inherent randomness of natural ecosystems.

This study aims to integrate ecological data – such as vegetation communities and their distribution concerning terrain slope, sunlight exposure, and proximity to water – into the gaming environment, to create an ecology-integrated gaming tool for collaborative landscape design. We present a structured workflow to guide the creation of ecologically realistic vegetation communities and enable interactive creation and visualization of restoration scenarios.

2 Developing the Tool

Using UE's PCG framework, we developed a workflow for an ecology-integrated gaming tool (Fig. **1**). To demonstrate the application, we used two case studies: a rural river (Allt Ghlinn Thaitneich) in Scotland, where riparian woodland is absent, and the proposed daylighting (i. e. opening-up) of a culverted urban stream in the Binz area of Zurich, Switzerland.

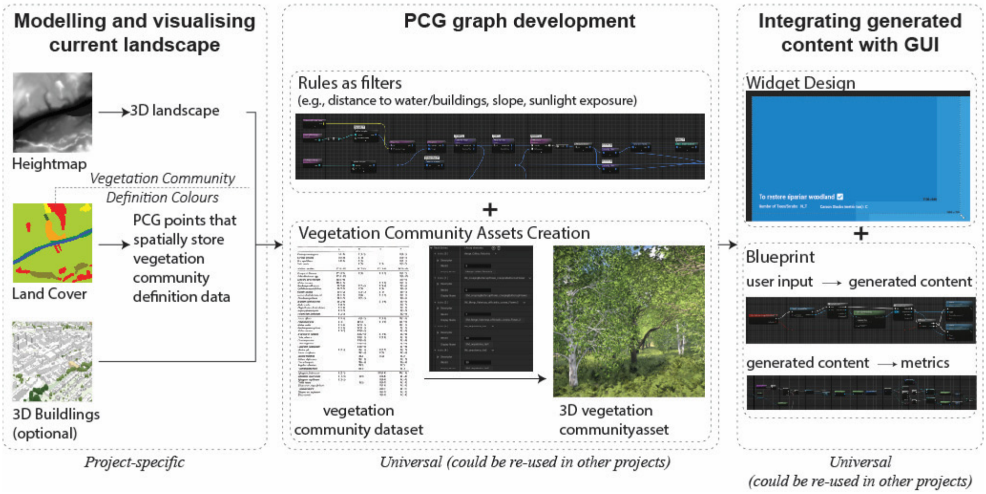

Fig. 1: Key workflow steps for developing the ecology-integrated gaming tool

In rural settings, for example in our Scotland study, current vegetation distribution was modelled using data from OpenStreetMap, local habitat map (Scottish Forestry Map) and on-site surveys. Each color on the map representing a distinct vegetation community type, such as "lowland birch woodland." Employing UE's PCG Biome Plug-in or similar algorithms, this map can be projected onto a grid of PCG points that spatially store vegetation community definition data, facilitating the creation of the existing terrain with vegetation.

In urban environments, 3D buildings and grey infrastructure can be modelled through either manual methods or automated 3D reconstruction techniques. The latter leverages advanced algorithms and relies on a large dataset of site photographs to generate accurate digital models of structures (Bódis-Szomorú, Riemenschneider & Van Gool 2016). Additionally, Building Information Modeling (BIM) data can also be imported, enabling integration of more detailed and comprehensive structural information into the virtual environment. For the Zurich case study, as an initial exploration of the workflow, manual modeling of façade details was carried out using SketchUp to create representations of the limited number of buildings in the study area, based on street view photographs and the 3D city model provided by the City of Zurich.

2.1 PCG Graph Development

The PCG graph is the core PCG blueprint in UE that defines procedural rules and parameters for dynamically generating content, ensuring flexibility and scalability in design workflows. We developed specific PCG graphs for different vegetation communities, allowing designers or players to select and apply them to generate the corresponding vegetation community in designated areas.

In rule-based systems, rules serve as filters that assess specific features or parameters – such as terrain slope, elevation, proximity to objects, or environmental variables – to ensure a particular location satisfies the criteria for content placement. Rule-based systems regulate element placement by utilizing ecological principles and incorporating randomization via noise and weight maps to achieve natural variation. This ensures that the produced biomes are both visually varied and ecologically consistent, reflecting natural distributions. Below are few instances of rules functioning as filters:

(1) A water distance filter calculates the difference between the Z-coordinates of points within a specified region and the elevation (Z-coordinates) of a defined water surface plane. This process filters out points based on specified height difference criteria, enabling the identification of areas corresponding to high, medium, and low water levels. These distinctions facilitate the appropriate allocation of vegetation types, such as aquatic, amphibious, riparian, and upland vegetation, ensuring ecologically accurate vegetation communities' generation.

(2) The slope filter uses the "Normal to Density" node to translate the surface normal vectors at specific terrain points into density values, excluding points where the normal vectors fall within a specified angular range. This ensures vegetation is placed only on slopes with appropriate inclination.

(3) In urban or rural environments with buildings or other grey infrastructure, the planar distance filter can identify areas within a specified distance from these structures. For instance, in the Canton of Zurich, regulations specify that trees must be planted at least 2 meters from the inner boundary of neighborhood roads and at least 0.5 meters from footpaths, free-standing sidewalks, or cycle paths (CANTON OF ZURICH 2020). These distance regulations can be incorporated into the PCG graph to ensure trees are not generated in prohibited locations, maintaining compliance with local regulations (Fig. **2**).

3D models of plant species, assigned corresponding weights to represent their proportions within the community, serve as "Mesh Entries" in the "Static Mesh Spawner," which is the final node in the PCG graph. This step outputs the plant meshes into the scene, completing the procedural generation process by populating the landscape with vegetation in accordance with the predefined vegetation community parameters and ecological rules. Species and their weights can be determined based on vegetation habitats or vegetation community classifications that encompass natural, semi-natural, and predominant artificial vegetation communities, such as British National Vegetation Classification (NVC) and Lebensraumtypologie TypoCH (a Swiss habitat typology system designed to describe and classify the natural and semi-natural habitats of Switzerland, simplified as TypoCH) (DELARZE & GONSETH 2015, JOINT NATURE CONSERVATION COMMITTEE 2020).

The NVC identifies 25 woodland communities including 7 wet woodland communities (W1-W7), as well as 28 swamp and tall-herb fen communities (S1-S28), along with their zonation and distribution. For example, W3 (*Salix pentandra–Carex rostrata*) and W4 (*Betula pubescens – Molinia caerulea*) occur in flushed areas near watercourses (RODWELL et al. 1991, RODWELL et al. 1995, BROADMEADOW & NISBET 2024). TypoCH also provides detailed classifications and distribution for riparian habitats, including categories such as 2.1. Banks with Vegetation, and 6.1. Swamp and Floodplain Forests, along with their respective subtypes. These survey-based databases provide detailed information on vegetation community characteristics and species composition, allowing for the prediction of plant species naturally suited to specific sites. The community model construction is based on the shrub and herbaceous cover and number of species observed in survey samples. Only species frequently appearing across survey samples or dominant in the communities are included in the model. Following the generation of the procedural environment, iterative testing was conducted to identify and adjust any elements that appeared visually unnatural.

Alongside vegetation communities, the PCG framework can automatically build rocks along the river randomly according to given rules or create artificial structures such as fences using input polylines and a 3D mesh of the unit, hence facilitating collaboration in landscape design.

Fig. 2: Visualization example of the Zurich case study

2.2 Integrating Generated Content with Graphical User Interface

The aim of this gaming tool is to allow stakeholders to co-design by selecting areas for certain restoration activities, and understanding ecological benefits and trade-offs of different interventions. Therefore, a Graphic User Interface (GUI) is needed to allow stakeholders to place specific vegetation types at specific locations, toggle new layers on and off to compare the modified landscape with the original, and visualize the metrics of different scenarios (Fig. **3**). Input parameters for scenario generation can be modified, and output indication criteria can be tailored to fulfil project requirements. Additionally, the GUI enables free movement within the scene, providing different viewpoints, such as first-person or bird's-eye view (KLEINSCHROTH et al. 2022), allowing users to explore the current and proposed future vision from multiple perspectives. This interactive setup enhances user control over landscape modifications and visual assessments.

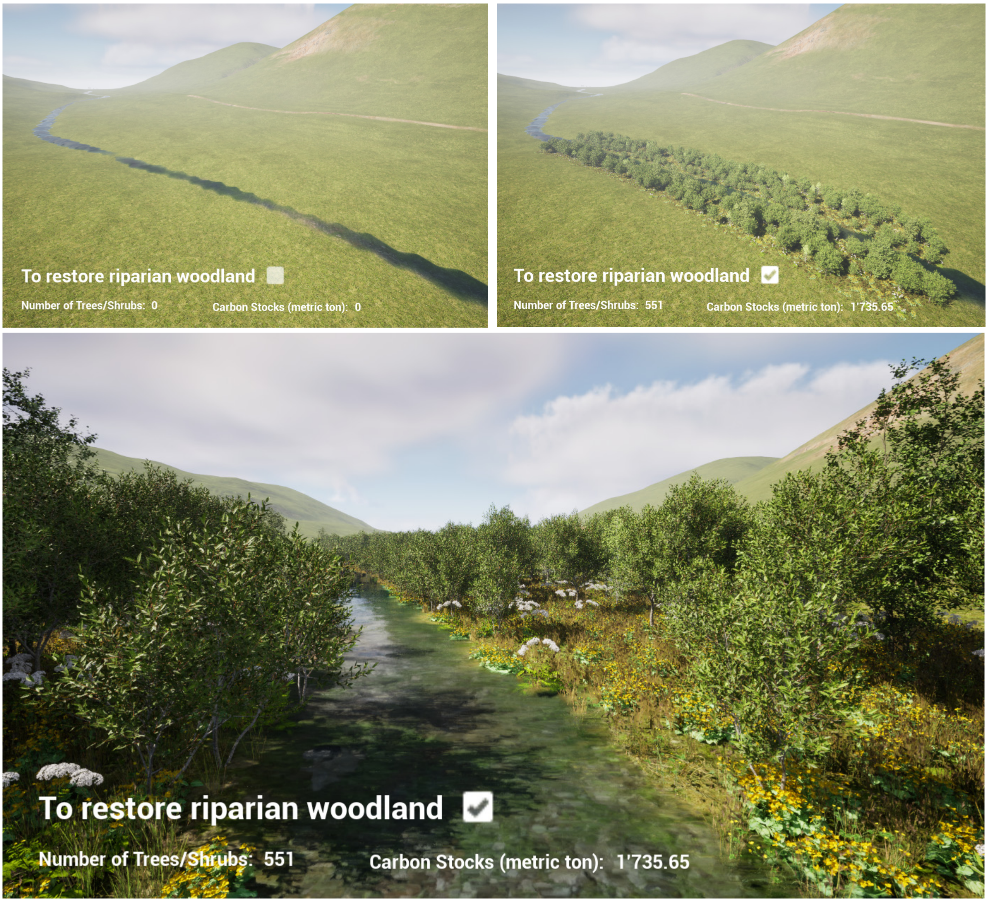

Fig. 3: Screenshot of the GUI from the Scotland case study, displaying the W3 Salix Pentandra-Carex rostrata woodland community

In UE, the integration of player control, PCG generation, and GUI feedback involves the following workflow: players interact with the environment through controls like movement or selection tools to specify areas for modification or click on checkbox to show and hide elements. These inputs are processed by the PCG graph, which dynamically generates content such as vegetation communities based on the player's choices. The results are then visually rendered in the scene in real-time. Simultaneously, the system calculates relevant ecological metrics, such as number of trees or shrubs planted and carbon stocks, and updates the GUI to display these indicators. This creates a feedback loop where players can observe the immediate impact of their actions, refine their designs, and make informed decisions about ecosystem restoration. This workflow enables an interactive and intuitive design process, combining ecological principles with practical visualization tools.

3 Discussion and Outlook

This study demonstrates the value of ecology-integrated game environments for participatory landscape design by merging ecological data with interactive, real-time simulations in game engines. Case studies on a rural river in Scotland and an urban stream in Switzerland confirmed the workflow's adaptability to various ecosystems and across scales. Such virtual landscapes, generated from 3D terrain models and land use/land cover data, integrate the advantages of GIS-based tools (BOROUSHAKI & MALCZEWSKI 2010), ensuring that collective decision-making reflects spatial layout while enhancing understanding through 3D visualizations. This study focuses solely on discussing the feasibility of using game engine technology with PCG framework for interactive visualization. The effectiveness and interpretability of the virtual vegetation community in will be assessed in the forthcoming study phase through expert evaluation and consultation. Meanwhile, user experiences and feedback will be analyzed in later studies through workshops as part of the proposed future research.

Unlike static renderers like Lumion and D5, which create fixed photorealistic visuals, UE supports dynamic interactions, enabling users to explore and modify landscape elements in real time. The GUI further allows users to easily input imagined future visions, balancing procedural randomness with design control. Compared to traditional parametric design tools like Rhino with Grasshopper, which rely on precision-centric control of parametric design, our ecology-integrated gaming tool based on game engine with PCG framework facilitates natural variability with minimal manual input, enhancing ecological realism for lay people to use. In the future, integrating machine learning methods, such as Generative adversarial networks could further improve procedural generation by adding complex environmental dynamics and player's behaviors (RISI & TOGELIUS 2020). In addition, UE's open-source flexibility allows scene and GUI outputs to be shared and reused, fostering rapid replication and broad application across projects, from education to ecological simulations for co-designing landscapes.

Despite the advantages, certain limitations emerged while using this ecology-integrated gaming tool. The approach relies heavily on a substantial library of detailed plant models to achieve ecological realism; to address this, procedural generation techniques can be used to create diverse plant variations from a smaller set of base models, reducing the need for an extensive model library. The current vegetation community creation process requires manual input, which can be labor-intensive. Integrating deep learning to summarize vegetation community composition and plant traits could potentially automate this step, reducing manual effort significantly. Future iterations could further benefit from integrating advanced environmental variables, such as dynamic weather patterns and seasonal changes, to simulate ecosystem fluctuations over time. Incorporating these elements would provide users with a richer understanding of temporal ecological processes, reinforcing the value as both an educational and design platform. The tool can quickly produce overall visualizations, which may be sufficient for public participation. However, for practical implementation, ecologists and design professionals are needed to further refine and detail the design based on the outcomes of participatory inputs.

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