Ecological Informatics 76 (2023) 102151

Contents lists available at ScienceDirect

Ecological Informatics

journal homepage: www.elsevier.com/locate/ecolinf

BeingAliveLanguage: Visualizing soil information from a design perspective to enhance multidisciplinary communication

Zhao Ma *, Teresa Galí-Izard

Department of Architecture, ETH Zurich, Zurich 8092, Switzerland

ARTICLE INFO

Keywords:
Soil texture visualization
Automated diagram generation
Landscape design
Parametric drawing

ABSTRACT

Soil forms the foundation for biotic and abiotic activities that shape landscapes over time. Effective communication and understanding of soil profiles, contents, and interactions with other systems such as vegetation and climate are crucial for multidisciplinary research and projects involving soil. A robust, comprehensible, and extendable visualization system is required to enhance communication across diverse disciplines, including landscape architecture, agronomy, and ecology.

This paper introduces the *BeingAliveLanguage*, an innovative, extensible visualization system for soil-centric information within a multidisciplinary communication framework. The system employs a fractal-based visual language to effectively convey vital soil information to professionals in various fields engaged in architecture, landscape design, and urban planning projects. The corresponding software, developed as a plugin for the Rhino-Grasshopper CAD environment, allows users to automatically generate easily understandable soil-centered diagrams using a node-based programming language. Designed to enhance communication in landscape, geoscience, and agriculture-related fields, the system provides critical information to support the design and decision-making process. We showcase the system's efficacy through two extensions and by utilizing the tool in multiple real-world projects.

1. Introduction

In response to the escalating significance of environmental concerns, fostering interdisciplinary integration is crucial for the development of innovative and comprehensive solutions. The imperative for educating professionals across diverse fields in enhancing dialogue beyond their respective disciplines has never been more pressing. As landscape architects and researchers, we have engaged in numerous projects that encompass a broad spectrum of disciplines, acknowledging the pivotal role of soil science within various ecological systems. Through collaboration with experts in disciplines such as soil science, ecology, water management, and urban planning, we have recognized the need for a coherent communication approach that efficiently conveys information across these fields. Accordingly, this paper proposes a visualization system utilizing computational algorithms to streamline the visualization and comparison of soil data, ultimately fostering effective communication and collaboration in multidisciplinary environments.

Within the domain of soil science, *digital soil mapping* (McBratney et al., 2000; McBratney et al., 2003) has emerged as a discipline that emphasizes the visualization of soil information. Leveraging computer-assisted techniques, this approach generates digital maps that illustrate soil types and properties, typically employing a diverse array of computational methods to streamline the map creation process. Current research highlights a wide range of applications for digital soil mapping, such as the incorporation of machine learning (Heung et al., 2016), the geographic representation of soil organic matter content (Wiesmeier et al., 2011; Yuan et al., 2021; Zhao et al., 2017), topsoil physical properties (Ballabio et al., 2016), the creation of metadata schema for soil-agricultural research data (Specka et al., 2019), and the development of general soil information systems at various global resolutions (Arrouays et al., 2014; Hengl et al., 2014; Hengl et al., 2017). These studies further demonstrate an extensive variety of visualization techniques employed in mapping soil data.

Conventional digital soil mapping in the environmental sciences primarily focuses on understanding resource and soil condition distribution from a geographical and spatial perspective at a relatively large scale. This focus may prove inadequate for specific projects in fields such as landscape design, urban planning, and resource management. These

* Corresponding author.
E-mail address: ma@arch.ethz.ch (Z. Ma).

https://doi.org/10.1016/j.ecoinf.2023.102151
Received 22 December 2022; Received in revised form 31 May 2023; Accepted 1 June 2023
Available online 7 June 2023

specific projects often require detailed soil information from a particular site, delving below the soil surface and taking into account varying depths. Technicians typically gather this information through soil surveys and present it as raw data to professionals. However, this format can create challenges in effectively communicating and collaborating across disciplines. Various research efforts have made strides in addressing these concerns: Yang et al. (2022) developed a framework for the preliminary delineation of soil profile horizons; Alqadad et al. (2017) documented several accidents that occurred during urban soil investigation due to outdated soil profile information; Temme and Vanwalleghem (2016) introduced a new model linking landscape and soil profile evolution based on sensitivity analysis; Pourabdollah et al. (2012) proposed a data exchange schema for soil and terrain data; Beaudette et al. (2013) developed algorithms to support data-driven approaches to common soils-related tasks.

In the realm of visualization, the chosen approach often depends on the target audience and the format of the source data. Given the limited literature on soil visualization outside of soil mapping, we conducted a broader survey of this topic within the general environmental and ecological context. A significant portion of such research falls into the *data visualization* category, which utilizes data obtained from various survey methods to reveal targeted information. Techniques such as reinterpretation, analysis, mathematical modeling, and optimization are employed to transform data into a format that highlights the intended information. The results of these studies are often code libraries in conventional data science programming languages (*Python* or *R*), which users can utilize and build upon (Araya et al., 2018; Nguyen et al., 2022; Serrano-Notivoli et al., 2022). Another type of visualization is typically created using web-based technology for monitoring purposes and can be accessed within an internet browser (Cope et al., 2017; Jarray et al., 2022; Deval et al., 2022). These studies often involve a backend online system that continuously collects and processes data before visualizing it on the frontend. Additionally, the utilization of software architectures that amalgamate multiple web-based technologies facilitates the creation of integrated pipelines for data processing and mapping (Zhang et al., 2022). This format enables users with minimal technical background to quickly obtain the information they seek. Additionally, research catering to specific needs employs customized visualization techniques, such as game engines (Cicekci et al., 2014), 3D modeling software (Filippucci et al., 2016), and more.

In this paper, we propose a soil-centered visualization system that functions as a diagrammatic language, acting as a communication tool to translate quantitative soil information among professionals from diverse backgrounds. This system is designed to strike a balance between simplicity and complexity, ensuring that essential information is neither neglected nor requires substantial effort to learn. The system should be capable of incorporating selected critical information based on limiting factors while also being adaptable to various forms for professionals from different disciplines and for different purposes. By enabling professionals to read and understand these diagrams, we aim to encourage a closer examination of soils and the surrounding ecological systems, fostering increased cross-disciplinary discussions in this realm.

Contributions. This paper presents the design and development of a visualization system, the *BeingAliveLanguage*, aimed at visualizing soil-related information for multidisciplinary research and collaboration. Our solution offers automated diagram generation that

- facilitates visualization, comparison of soil profiles, and integration of additional soil data,
- offers integrated extensions for wider applications, including Bagnouls-Gaussen diagrams and dynamic root growth, and
- empowers users to generate diagrams using a node-based, flowchart programming interface for diverse scenarios.

Our proposed visualization system introduces features that are unparalleled in previous software, significantly expanding the creative and illustrative potential of computational visualization for scientific information in geoscience and ecology, reaching a wider audience. The design orientation of the *BeingAliveLanguage* and its utilization of *node-based* programming interface enable swift iterations and scenario-based parametric design – a facet not addressed by other soil visualization tools. By bridging the gap between scientific and design disciplines, the *BeingAliveLanguage* aims to provide a visualization system adept that effectively conveying scientific information, fostering interdisciplinary collaboration and understanding.

This paper is structured as follows: Section 2 introduces the methodology and definition of the visual system, along with two possible extensions of the system. Section 3 details the computational algorithms derived from the definition, which support the auto-generation of the diagrams. Section 4 outlines the concept of node/flowchart programming and the software development environment. Section 5 showcases results generated by the software using surveyed soil data from real projects and discusses various challenges. Finally, Section 6 offers conclusions and outlines several future research directions.

2. Methodology

This section outlines the *BeingAliveLanguage* framework for visualizing soil profiles and soil water content. Additionally, we present two extensions built upon this visualization system. Our objective is to establish *BeingAliveLanguage* as a foundational diagrammatic system for soil-centered information, thereby promoting the development of further multidisciplinary applications within the community.

2.1. Soil composition and representation

2.1.1. Soil separates

A prevalent method for classifying soil types is the utilization of the USDA soil texture classification system (García-Gaines and Frankenstein, 2015). This ternary system enables the determination of one of the 12 textural classes by inputting the proportions of the three primary soil particle groups, known as “soil separates”: sand, silt, and clay (Fig. 1).

Previous studies have demonstrated a diverse array of applications for this ternary diagram, including the representation of hydraulic information (Groenendyk et al., 2015) and subsurface soil properties (Hu et al., 2004), the collection of agricultural data for dynamic soil texture prediction (Aarthi and Sivakumar, 2020), and the assessment of sensor

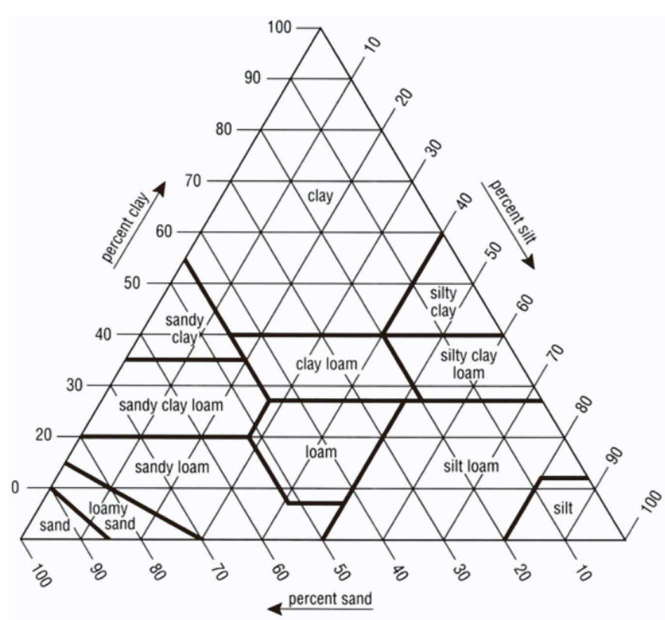

Fig. 1. USDA soil texture triangle (NRCS, 1993).

data for soil texture estimation (Andrade et al., 2022).

In alignment with the objectives of the *BeingAliveLanguage*, which seeks to present soil data in a manner that is both visually interpretable and scientifically meaningful, we aim to develop a geometric system capable of reflecting soil texture and the aggregation stage of soil particles. Intentionally associating the geometric system with the USDA chart, we select a triangular shape as the fundamental unit. We apply a fractal relationship to the triangle to generate triangle units in three distinct sizes, while preserving the global tessellation capability. Consequently, we can construct sectional soil diagrams corresponding to specific soil profiles (Fig. 2). By aligning the vertices of the side triangles, diagrams of given soil horizons can be assembled into larger diagrams representing more intricate soil compositions.

2.1.2. Associated components

The three soil separates constitute only the mineral matter component of soil, which is merely one of its constituents. The remaining three components include water, air, and organic matter, all of which play a crucial role in supporting biological activities. Existing research demonstrates efforts to visualize these elements at varying scales: various tomography technologies (Moradi et al., 2011; Menon et al., 2007; Zarebanadkouki et al., 2014) and magnetic resonance imaging (MRI) techniques (Pohlmeier et al., 2013; Robert et al., 2014) have been employed to accurately quantify and visualize the interactions between water and plant roots at the micro-scale; more cost-effective fieldwork techniques have been utilized to visualize preferential flow in water-repellent sandy soils (Ritsema and Dekker, 2000); modeling and statistical approaches are also employed to analyze and visualize soil quality (Villamil et al., 2008).

Although these techniques offer various possibilities for observing specific interactions between soil constituents and plants or analyzing particular soil properties, the *BeingAliveLanguage*'s scope bridges the gap between scientific and design disciplines, striving to deliver a visualization system that effectively translates general information.

In contrast to the methods employed in the aforementioned literature, our focus lies in visualizing soil water content across diverse soil profiles using profile-associated data. Such specific water data can be found in multiple resources (Saxton and Rawls, 2006; Datta et al., 2017; Vogel et al., 2019), and we refer Datta et al. (2017) for the quantified soil water content information corresponding to each soil type (Fig. 3).

As shown in Fig. 4, we also integrate two supplementary parameters, namely the "current (soil) water content" and the "organic matter", due to their significant relavance to climate and ecological processes. The former parameter is employed to depict the the soil water content of soil at a specific location and time, while the latter is utilized to indicate the quantity of organic materials in the soil. The density of these lines varies across different units, enabling the visualization of the distribution of organic matter within a soil horizon.

2.2. Extension

A key advantage of the *BeingAliveLanguage* visualization system is its extensibility, which has been purposefully designed. Our objective is to establish a shared foundation for multidisciplinary communication in soil-related research and projects, catering to a range of requirements. In this section, we showcase two extensions: the integration of the climate graph, such as water balance graphs and Bagnouls-Gaussen diagram (or the Gaussen diagram) (Bagnouls and Gaussen, 1957), to visualize climate data (the variation in soil water content throughout different months of the year); and the integration of root growth simulation into our tessellated soil diagram, providing a conceptual representation of the interaction between plant roots and soil. We anticipate that future users will further expand these extensions to suit their specific applications.

2.2.1. Climate graph integration

In multidisciplinary collaboration, it is crucial to connect soil information with other data, such as climate data, to provide a more comprehensive understanding of various biological and ecological processes. *BeingAliveLanguage* has the ability to integrate climate data extracted from water balance graphs or Bagnouls-Gaussen diagram,[1] which describes the relationship between temperature and precipitation, to illustrate the limiting factors (mainly duration and intensity of drought) for plant growth and reproduction (Filippi, 2007).

For example, given a specific geographic location, it is possible to acquire the monthly temperature and precipitation data from the associated Bagnouls-Gaussen diagram. Subsequently, potential evapotranspiration can be estimated using temperature-based methods[2] (Wanniarachchi and Sarukkalige, 2022) and corrected according to the latitude of the location (hours of light). This information enables the calculation of the soil's hydric balance, including surplus, deficit, or reserved water amounts, for a given soil depth[3] (Samani, 2000). Moreover, the soil water content ratio can be determined by taking into account the soil texture and maximum reserved water amount, and subsequently represented in our visualization system.

The integration process described above is illustrated in Fig. 5, where the water balance graph is overlaid on the Bagnouls-Gaussen diagram, combined with the calculated information for a typical geographic location. The comparison of soil water content at two different soil depths during two specific months, namely May and October, demonstrates the effectiveness of the *BeingAliveLanguage* in visualizing the combined information of soil, water, and climate using a unified visual language.

The integrated approach offered by the *BeingAliveLanguage* not only enhances our understanding of the interplay between soil, water, and climate factors but also uncovers insights from various disciplines. By visualizing these interconnected elements, the system supports more informed decision-making in the context of landscape design and management.

2.2.2. Root growth integration

Soil serves as the fundamental living environment for most vegetation. Plant root systems interact with the soil (Jin et al., 2017) to obtain essential water and mineral resources necessary for their metabolic activities while releasing byproducts into the soil. Kuzyakov and Blagodatskaya (2015) propose a detailed view of the microbial processes happen occuring in the rhizosphere and their ecological relevance. In one of our previously published articles (Galí-Izard et al., 2022), we described the relationship between a root and its surrounding environment from a narrative perspective. In this paper, we aim simulate the growth of a root from a technical and diagrammatic standpoint.

To graphically represent root growth within a triangular grid as described in this paper, a *map* providing topological information of the base grid is typically needed. Various approaches have been employed in existing research to build maps depending on the specific objectives. For instance, mixed integer programming is widely used for automated metro map generation (Oke and Siddiqui, 2015; Xu et al., 2022; Nollenburg and Wolff, 2011), with derived or extended optimization approaches also appearing in other sources (Stott et al., 2011). These

[1] The Bagnouls-Gaussen diagram, also known as the ombrothermic diagram or Bagnouls-Gaussen graph, is a graphical representation of climate, specifically designed to study the aridity of a region. It was developed by French scientists Frederic Bagnouls and Henri Gaussen in the 1950s. The diagram plots two critical variables: temperature and precipitation, on a monthly basis.

[2] There are two distinct sets of evapotranspiration estimation methods available. In our case, we utilize a temperature-based method, specifically the *Thornthwaite equation*.

[3] Computation related to these factors has also been developed as an extra component into the *BeingAliveLanguage* system.

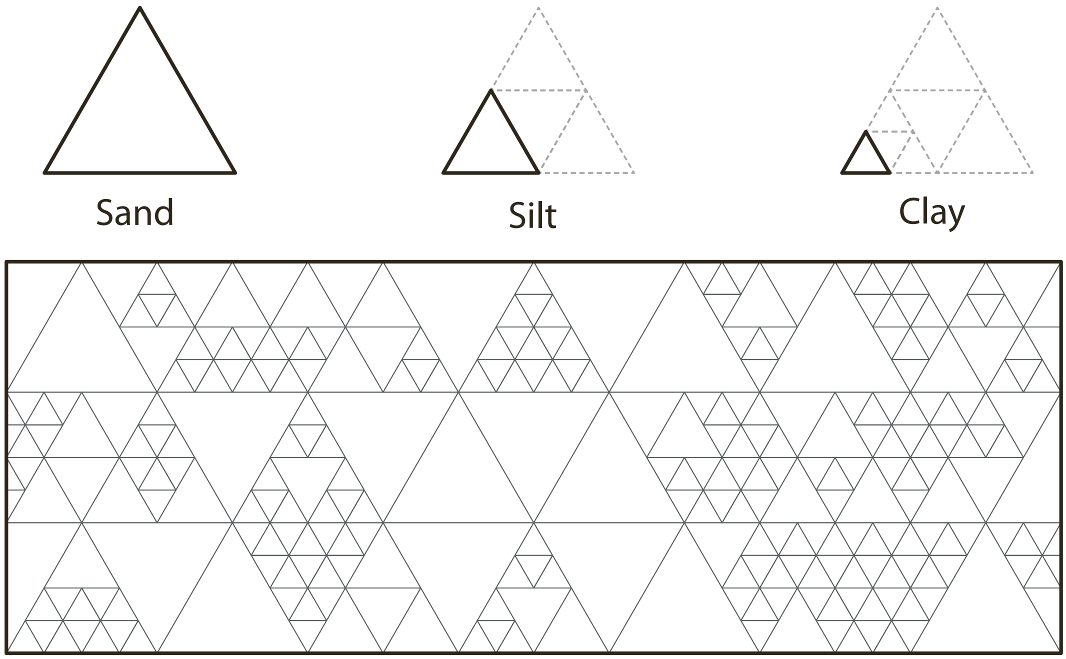

Fig. 2. Top: fractal relationship of the three soil separates. Bottom: A tessellated soil distribution using 3 different sized triangles.

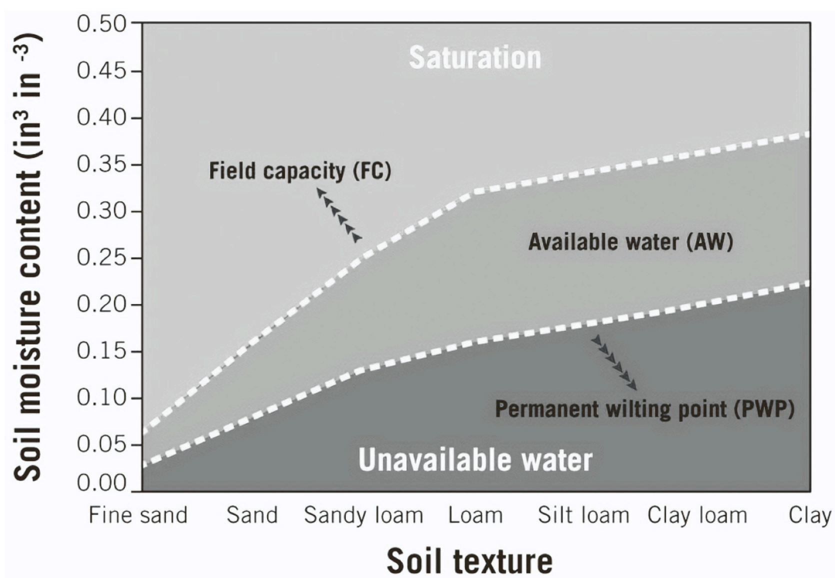

Fig. 3. The relationship between soil water content and different soil textures (Silva et al., 2019).

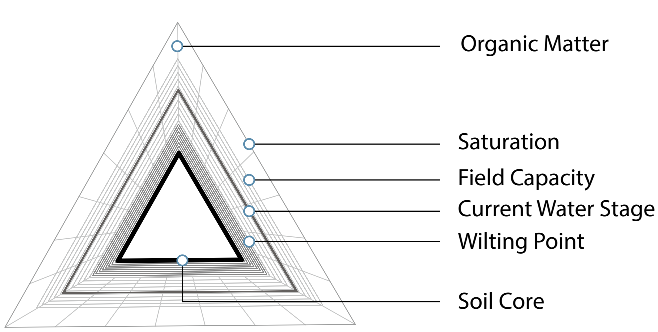

Fig. 4. Definition of a single soil unit.

graph-based approaches focus on the topological relationships between elements. In contrast, Isikdogan et al. (2017) developed an automated river mapping technique from remote sensing data based on the Cartesian system, where actual scale and distance are of greater importance.

In this paper, to establish the connection between the root and the soil diagram, we extract the outer triangles of the particle units and treat them as a *graph*$G\{V,E\}$. We then restrict the root to grow only along the vertices V and edges E, using the Euclidean relationship between vertices to control the root's scale. Consequently, we can simulate root growth in a stepwise, probability-based manner within our soil diagram and associate the root with various plants. We present several examples in Figs. 12 and 13, and describe the detailed algorithms in Section 3.3.

Although we acknowledge that there are more root types in reality, based on the *Raunkiaer system* (Raunkiær, 1934), a detailed exploration of these types is beyond the scope of this paper. We recommend that

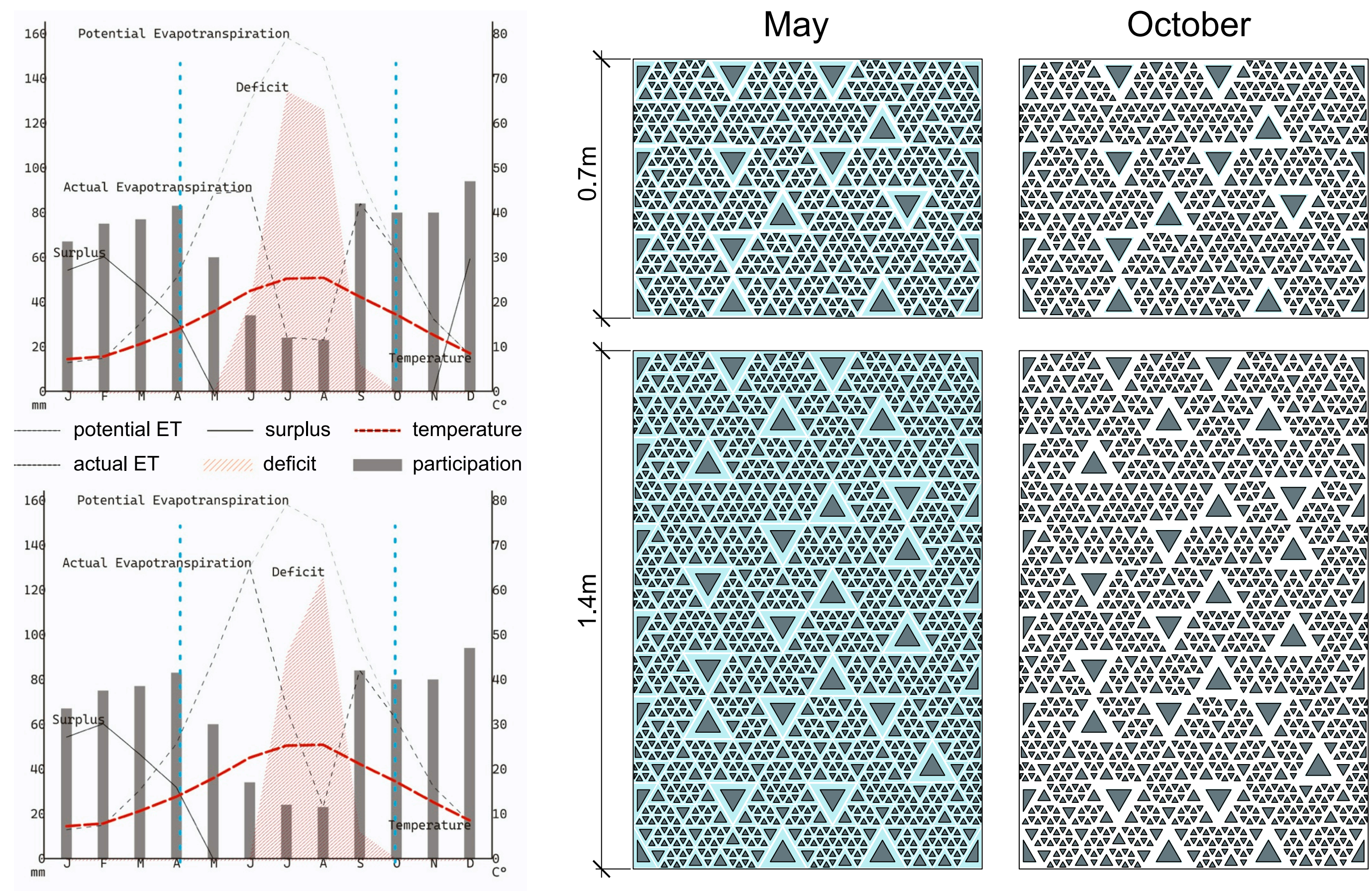

Fig. 5. Utilizing the *BeingAliveLanguage* to visualize soil water content for two specific months (right), based on the latitude of a particular geographic location and its temperature and precipitation data extracted from its Bagnouls-Gaussen diagram (left, with additional information overlaid. Credit: Luke Harris).

interested readers refer to the corresponding literature for more information on the subject.

3. Algorithm and implementation

This section elucidates the fundamental algorithms we devised to underpin the definition and methods detailed in Section 2. These algorithms have been implemented in the *BeingAliveLanguage* software as a plugin for a widely-used CAD platform. The particular software environment is discussed in Section 4.2.

3.1. Soil type clasification

In Section 2.1.1, we discussed employing the USDA soil texture diagram to classify soil types according to the proportion of soil separates. This 2D diagram establishes a graphical relationship among various soil types, which can be abstracted into an algorithm to automate the soil classification process.

The algorithm is derived by examining the classification criteria for each soil type and translating them into mathematical terms. Table 1 presents the complete results of this deduction, which have been encoded into the *BeingAliveLanguage*. It is worth noting that, due to the intricate shapes of *loamy sand*, *silty loam*, and *sandy loam*, the corresponding determining conditions for these three textures are also more complex than others and necessitate special consideration.

Upon accurately identifying the soil texture, we can extract the soil water holding capacity based on existing geographical data (Datta et al., 2017). The definition of the soil unit (Section 2.1.1) enables the proper integration of such data, allowing for automatic generation of detailed diagrams containing all relevant information for the current soil texture.

Table 1
Soil type determinating condition based on ratio. (with additional condition: $r_{\text{sand}} + r_{\text{silt}} + r_{\text{clay}} = 1$).

Soil Type	r_{sand}	r_{silt}	r_{clay}
Sand	$(0.5r_{\text{clay}} + 0.85, 1.00]$	NA	$(0.00, 0.10]$
Silt	NA	$(0.80, 1.00]$	$(0.00, 0.14]$
Clay	$(0.00, 0.45]$	$(0.00, 0.40]$	$(0.40, 1.00]$
Sandy Clay	$(0.45, 1.00]$	NA	$(0.35, 1.00]$
Silty Clay	NA	$(0.40, 1.00]$	$(0.40, 1.00]$
Clay Loam	$(0.20, 0.45]$	NA	$(0.27, 0.40]$
Silty Clay Loam	$(0.00, 0.20]$	NA	$(0.27, 0.40]$
Sandy Clay Loam	$(0.45, 1.00]$	$(0.00, 0.27]$	$(0.27, 0.35]$
Loam	$(0.00, 0.53]$	$(0.28, 0.50]$	$(0.07, 0.27]$
Loamy Sand	$\neq g\text{Sand} \wedge r_{\text{sand}} \in (r_{\text{clay}} + 0.70, 1.00] \wedge r_{\text{clay}} \in (0.00, 0.15]$		
Silty Loam	$(r_{\text{clay}} \in (0.00, 0.27] \wedge (r_{silt} \in (0.5, 0.8])$ $\vee$ $(r_{\text{silt}} \in (0.80, 0.1] \wedge r_{\text{clay}} \in (0.14, 1.00])$		
Sandy Loam	$r_{\text{clay}} \in (0.00, 0.07] \wedge r_{\text{sand}} \in (0.53, 1.00] \wedge r_{silt} \in (0.00, 0.50]$ $\vee$ $\neq g(\text{LoamySand}) \wedge r_{\text{clay}} \in (0.00, 0.02] \wedge r_{\text{sand}} \in (0.53, 1.00]$		

The outstanding question pertains to the method for combining these units into a diagram that accurately represents the corresponding soil horizon.

3.2. Soil diagram automation

In the following, we outline the process of generating a soil horizon diagram that accurately represents the distribution of three soil separates akin to the example in Fig. 2. To accomplish this, we require the correct ratio data of the soil separates ($r_{\text{sand}}, r_{\text{silt}}, r_{\text{clay}}$) along with two additional input parameters: a specified rectangular boundary (S_{border}) and a subdivision density ρ_{subdiv}.

The algorithm initially subdivides the boundary S_{border} into a series of regular triangles based on the density parameter ρ_{subdiv} (additional post-processing techniques are applied to align triangles near the borders). Subsequently, it performs two iterations of the “selection + subdivision” processes to determine sand and silt: it selects a subset of triangles that corresponds to the area ratio, and then subdivides the remaining triangles into four smaller fractal ones. Following these two iterations, there should be three levels of triangles, each representing the soil separates of sand, silt, and clay, respectively.

Upon completing this step, we can incorporate other soil compositions, as computed by the algorithm in Section 3.1, into the diagram, thereby generating a comprehensive visual representation of the given horizon. The pseudocode of the entire algorithm is provided in Algorithm 1.

Algorithm 1 Soil Diagram Generation

```
Require: r_sand, r_silt, r_clay, S_border, ρ_subdiv
Ensure: r_sand + r_silt + r_clay = 1, S_border is rectangular
  function SUBDIVIDE S_border, ρ_subdiv
    Subdivide S_border into T_all
    T_prepared = T_all
    for k←1 to N in [r_sand, r_silt] do
      Select T_lv.k from T_prepared : r_k * A_border = A_{T_lv.k}
      T_prepared = FRACTALDIVIDE(T_all \ T_lv.k)
    end for
    DETERMINE “soil type” from Table 1
    CREATE Soil Diagram
    CREATE Water Content
    CREATE Organic Matter          ▷optional
  return Diagram
end function
```

It is essential to recognize that the *BeingAliveLanguage* system comprises numerous individual components, and combining all the information can result in a highly compacted diagram. In real-world applications, users can choose a subset of the information (e.g., soil separates and wilting point) tailored to their specific requirements, thus producing diagrams with improved readability.

3.3. Root grow simulation

The primary factor influencing a root's growth direction is gravity. Given that we determine the root should grow between the soil particles without breaking them, the triangle vertices naturally become the locations where a root grows from or towards. Consequently, the “actual” topology graph $G\{V,E\}$ employed by a root is similar to the one depicted in Fig. 2.Bottom.

Since such a diagram consists of three differently sized triangles, each vertex v_0 is connected to 4 or 6 neighboring vertices v_i, with equal or unequal Euclidean distances $\|\vec{d_i}\|$. For each vertex, we store the direction and the distance of these neighbors and construct a hash table for the data to enable rapid querying.

For each growing step, we apply a probability function, typically a normal distribution, in all directions. This results in a probability-based growth effect towards a preferred direction while allowing for a certain degree of randomness. At each step, we only permit unary or binary branching to neighboring vertices. To control the overall size of the root, we employ a global radius R_{grow} to limit the accumulated Euclidean distances from the starting root vertex to the farthest leaf vertex (Fig. 6).

We demonstrate this algorithm with more examples in Section 5.1.

4. Software design and usage

While developing the *BeingAliveLanguage* as a versatile visual system for promoting multidisciplinary communication, we expected that users can employ the system independently or alongside other digital drawing tools. Consequently, we decided to integrate our software within a CAD environment, allowing for direct modification of results or additional development on top of our system. The availability of *node-based programming* helps us achieve this goal, offering a pliable and accessible platform for users to engage with and build upon our visual system.

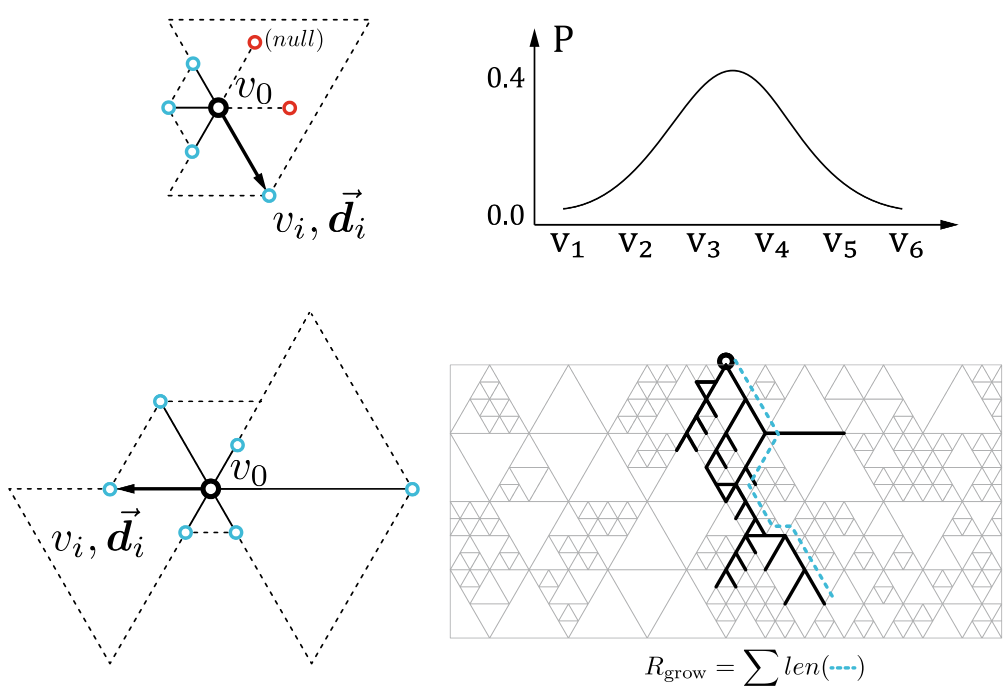

Fig. 6. Vertex relationship and parameters in probability-based root growing. Left: The two typical cases where a vertex has either 4 or 6 neighbors (to keep data structure aligned, we use a null value if the neighbouring vertex does not exist); TopRight: Normal distribution for vertex probability; BottomRight: Using R_{grow} for global root radius control.

4.1. Node-based programming

Node-based programming, also referred to as *flowchart programming*, constitutes a category of *visual programming language* (VPL) that enable users to construct programs by graphically connecting a sequence of "nodes" for the execution of logical operations, as opposed to delineating them through textual code. This methodology provides a more intuitive and accessible means for designing and developing software, particularly for individuals possessing limited programming expertise. Presently, it is among the most prevalent visual programming models employed across diverse fields, permitting users, including children, with minimal programming knowledge to participate in programming activities effortlessly. Fig. 7 depicts an array of prominent software applications for visual programming (encompassing both node-based and non-node-based) spanning various sectors and industries.

The core principle of node-based programming pertains to the employment of an abstracted node model for the representation of data or a computing operator. Each "node" accepts zero or multiple *inputs* and yields *outputs* subsequent to executing a *computing operation*. The scope of these computational operations encompasses elementary arithmetic tasks as well as intricate customized functions necessitating considerable computational resources. (Fig. 8).

The intricacy of project development for users is predominantly contingent upon the assortment of *nodes* supplied by both the software development team (intrinsic default functions) and community developers (plugin functions). A robust platform typically reaps the advantages of an active community-driven ecosystem, encompassing hundreds of plugins contributed by an array of sources. This, in turn, enables an extensive scope of functionality and customization for the end-users.

4.2. Development environment

For the *BeingAliveLanguage*, we chose the Rhino[4]-Grasshopper[5] platform as the base environment. This platform is widely accepted for 3D modeling and parametric design in the architecture, landscape, and computer-aided design community. We implemented our algorithms as a plugin for the Grasshopper environment (Fig. 9), leveraging Rhino's modeling and drawing API alongside Grasshopper's default computing units to produce illustrative diagrams.

We adhere to several software development best practices, such as version control, issue tracking, and pull requests via *GitHub*, to guarantee a reliable development process. Additionally, we employ the *MkDocs*[6] system to generate HTML documentation, which is accessible through a permanent website[7] hosted by ETH Zurich.

The majority part of the *BeingAliveLanguage* has been developed using the `C#` language within Microsoft's.NET Framework and is integrated into Rhino's plugin ecosystem. The plugin can be installed on *Rhino v7* + utilizing its build-in package management system.

In terms of computational complexity, the two most resource-intensive processes are building the soil map and simulating root growth. By making appropriate choices for data structures (Hash map and K-d tree) and leveraging parallel computing, we have successfully reduced the computational complexity to an $O(n\log n)$ level. Our experiments demonstrate that constructing a soil map containing approximately 1 million vertices takes less than 10s on a modern i7-8550U laptop with 16 GB RAM. Generating diagrams at a moderate scale allows for almost instantaneous feedback and enables an interactive design process.

[4] Rhinoceros 3D:https://www.rhino3d.com.

[5] Grasshopper 3D:https://www.grasshopper3d.com.

[6] https://www.mkdocs.org.

[7] https://beingalivelanguage.arch.ethz.ch.

5. Results

5.1. Demonstrations

We have evaluated the effectiveness and interactivity of *BeingAliveLanguage* during diagram creation across various projects, generating soil diagrams that incorporate other elements for diverse scenarios. The subsequent examples showcase these applications.[8] As we mentioned in Section 1, the *BeingAliveLanguage* visualization system is designed for flexibility, enabling users select a wide range of available computing units. Consequently, the final appearance of the diagram largely depends on the user's choice of information to display.

Soil Profile Comparison. On numerous occasions, it is necessary to visualize quantitative soil data obtained from field surveys or lab analyses and convey this information with various stakeholders. Indeed, one of the primary purposes of developing *BeingAliveLanguage* is to facilitate communication between soil scientists and professionals from other disciplines, such as architecture, landscape design, urban planning, using a unified visual tool. Typical applications for visualizing soil information involve comparing soil conditions across different soil horizons, contrasting multi-horizon soil profiles, and illustrating various aspect within the soil, such as soil water content and organic matter. In the following, we present two examples that demonstrate the effectiveness of the *BeingAliveLanguage* in addressing these needs.

In the first example, we demonstrate that the *BeingAliveLanguage* visualization system is capable of aligning well with existing soil survey results by creating diagrams based on existing research. Fig. 10 presents the redrawn diagrams and the soil sectional photos side by side, where the diagrams facilitate comparisons between different soil profiles. It accurately represents the actual conditions and conveys essential information from soil science, establishing a solid foundation for communicating information across various disciplines.

Since the soil profiles in Fig. 10 exhibit minimal differences and do not display significant contrasts across soil horizons within the same soil profile, we present a second example featuring soil profile diagrams from two geographically distant locations, Fusagasugá, Colombia, and Suterranya, Spain. The contrasts across soil horizons, as well as between different soil profiles, are clearly demonstrated in Fig. 11.

Integration with Extra Environmental Factors. The *BeingAliveLanguage* has been purposefully designed for flexibility and extensibility, making it highly valuable for integrating work from various disciplines and fostering impactful multidisciplinary collaborations. In this section, we present two examples showcasing how this system has been utilized in such contexts. It is important to note that in different examples, we have deliberately colored the selected information based on the specific information we aim to deliver, further emphasizing the adaptability and customization potential of the *BeingAliveLanguage* system for diverse applications.

Fig. 12 displays the results from two different locations in the Senan region of Spain. In collaboration with local researchers, we examined environmental factors such as soil conditions and vegetation to plan long-term land management strategies. These diagrams facilitated communication with local experts from related fields, providing a shared visual language that transcends disciplinary boundaries.

The second example illustrates the change in soil conditions over time due to interactions with the environment and their impact on animal husbandry. Fig. 13 showcases the relationship between horse hoof treatment and soil conditions, demonstrating that well-conditioned soil can support horses' foot health by allowing them to walk with bare feet. These diagrams facilitate communication with scientists in the field of animal husbandry, promoting interdisciplinary understanding and

[8] The two projects are part of a more extensive, ongoing initiative that has spanned several years. For more information:https://thegarden-senan.arch.ethz.ch.

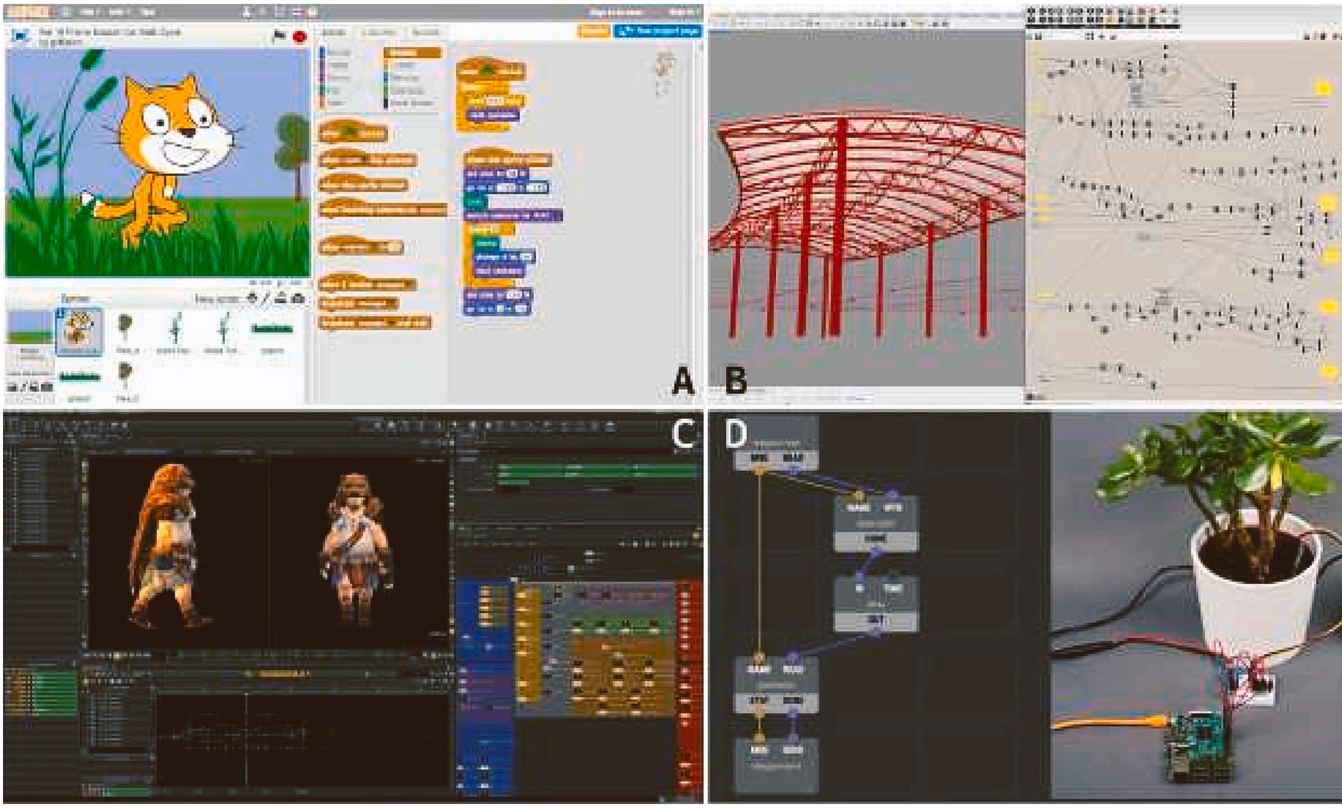

Fig. 7. Various Visual Programming Platform. A: Scratch, a VPL for kids, not node-based; B: Rhino-Grasshopper, a node-based visual programming environment for CAD; C: Houdini, a node-based platform for the CG industry; D: XOD, a node-based VPL for microcontrollers.

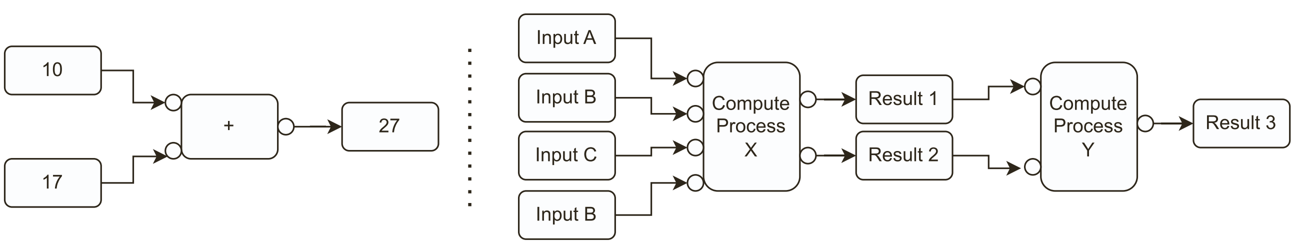

Fig. 8. A node-based computing process. Left: a simple addition with two inputs and one output; Right: two consequtive customized computing process that involve multiple input/output.

collaboration.

5.2. Discussion and limitations

The presented results have many implications to consider for many future research directions. As the software is developed along several projects, some of the functionalities are not implemented into a "perfect" state. Moreover, as we have just started to use this visualization system during our collaboration with professionals from other disciplies, the *BeingAliveLanguage* is still in its early phase and activately collecting feedback.

5.2.1. A unified visual language for effective soil utilization in landscape projects

In addition to the *digital soil mapping* review in Section 1, a substantial amount of research on soil/landscape management also utilizes "mapping" or GIS-supported approaches, as it is one of the most effective ways to associate collected data with geographic information (Qu et al., 2013; Pechanec et al., 2015). These map-based studies effectively reveal the interrelationships of the data associated with geographic distribution, providing a valuable overview for targeted users or professionals. However, little research focuses on projects at the scale of building, landscape, or urban block. Resource distribution at such scales does not vary significantly geographically but varies considerably at different depths within the soil. The collected data is limited and does not differ substantially on geographic maps. Furthermore, multidisciplinary collaboration across various disciplines is more intense between different parties within these projects.

The *BeingAliveLanguage* is our attempt to fill this gap by creating a unified visual language that facilitates effective communication about proper soil use and related resources across various professional disciplines. To the best of our knowledge, it is the first of its kind specifically designed to target communication of soil information among multidisciplinary professionals. This challenge also pushes us to develop visualizations that deliver information with the appropriate level of detail for the intended audience: determining the right balance of qualitative and quantitative data to extract, abstract, and present, and how to tailor the visualizations for different audiences (soil scientists, architects, landscape architects, agronomists, etc.) within a unified framework.

Unlike the tools or programming language packages we reviewed in

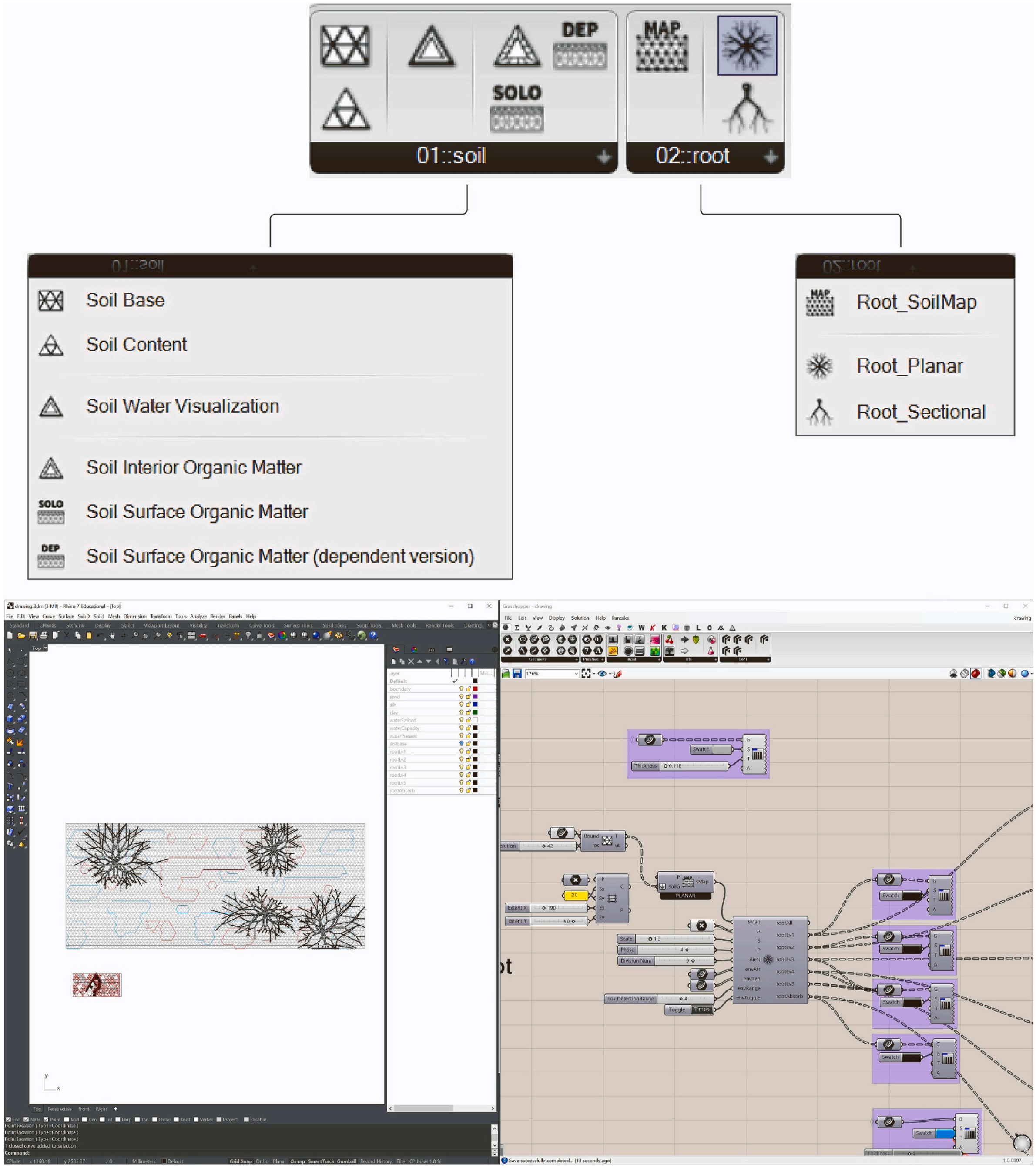

Fig. 9. The *BeingAliveLanguage* plugin. Top: The "nodes" provided by the plugin; Bottom: Using the plugin in a diagram development process.

Section 1, our approach draws knowledge from design and computer graphics fields to create software specifically designed for a CAD platform, allowing for extended development. Users can select specific components separately and compose independent diagrams/drawings or integrate them into drawings of existing projects. The reader should have already noticed the varied emphasis on visualized information in the figures presented throughout this paper. This flexibility enables the *BeingAliveLanguage* to cater to a wide range of user needs and preferences, fostering effective communication and collaboration among professionals from diverse disciplines.

5.2.2. Challenges and potential for extensibility

While our software is developed on a specific CAD platform, it necessitates that users have a basic familiarity with both CAD environments and node-based programming. Once these prerequisites are met, users typically experience a relatively smooth learning curve when creating visualization diagrams with the *BeingAliveLanguage*, as evidenced by our students. Interpreting these diagrams also demands a fundamental understanding of soils, such as soil separates, water content, and organic matter. However, this information can be easily communicated to professionals from various backgrounds. One of the advantages of our approach is that once created, the drawings can be documented alongside the project as vector-based digital assets.

A significant hurdle for the *BeingAliveLanguage* lies in achieving its widespread adoption across various disciplines, which we are actively promoting. By engaging in an increasing number of collaborations, our goal is to establish this visualization system as a standard for visualizing soil-centered information in multidisciplinary projects.

Contrarily, our system, which is designed to provide visualizations for specific geolocations with detailed soil information and manually

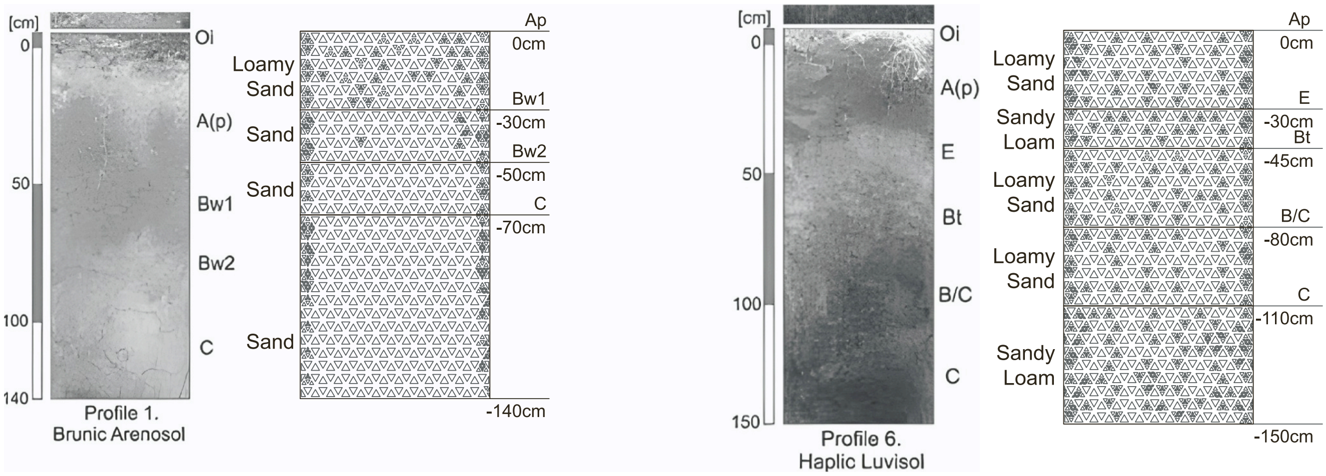

Fig. 10. Comparison across two soil profiles extracted from Przewoźna (2014). The photos has been processed into grayscale to eliminate visual disturbance.

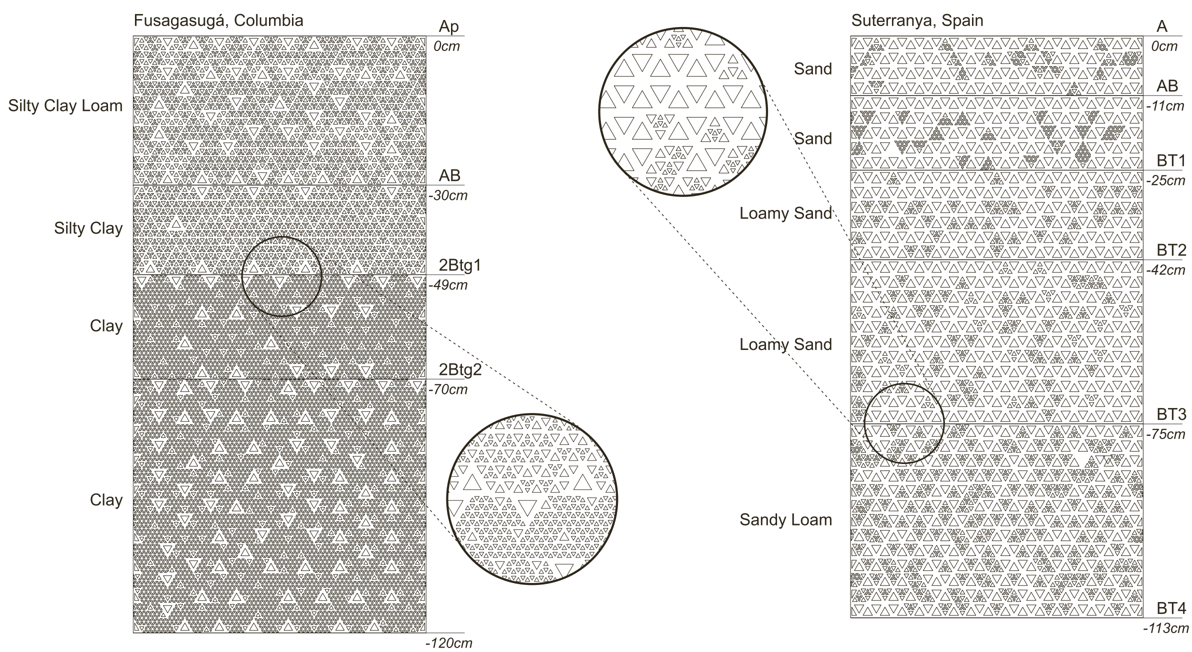

Fig. 11. Soil diagrams comparing two soil profiles from the Fusagasugá, Columbia and Suterranya, Spain. Difference across soil horizons (within the same soil profile) or geographical locations (between the 2 soil profiles) can be clearly identified.

retrieved local climate data, envisions potential avenues to exploit existing remote sensing data and web-based APIs. For instance, the utilization of resources such as *Crop-CASMA* (Zhang et al., 2022) for US soil moisture data can be beneficial. This could lead to the development of integrated data streaming pipelines for visualizing soil information at varying degrees of granularity. Not only would this augment the interoperability of our system, but it would also foster enhanced multidisciplinary communication at the developmental stage, consequently bolstering collaborations across fields. Nevertheless, the prospect of identifying a unified data framework with global applicability remains uncertain to us.

Although we have demonstrated only two extensions of the *BeingAliveLanguage*'s usage, we envision numerous opportunities to expand the system, incorporating vegetation systems, better-integrated climate factors, a more extensive collection of root systems, and more. All of these enhancements will require additional time for validation and integration. As we receive feedback and learn about the needs of various professions, the *BeingAliveLanguage* will continue to evolve and improve to better serve the diverse needs of interdisciplinary collaboration.

6. Conclusions

This paper presents the *BeingAliveLanguage*, a first-of-its-kind, extensible visualization system for soil-centered information in a multidisciplinary communication context. The system develops a fractal-based visual language to effectively convey essential information about soil and its related resources to professionals from various backgrounds. Unlike most resource mapping tools that associate targeted data with geographic maps, the *BeingAliveLanguage* focus on projects at the scale of architecture, landscape design and urban planning, where soil data varies less significantly across geographic locations but in depths, generating soil sectional diagrams. The extensibility of the *BeingAliveLanguage* is demonstrated by two examples: the integration of Bagnouls-Gaussen diagrams and geographically-relevant climate data, and the abstracted simulation of root systems within the proposed soil system.

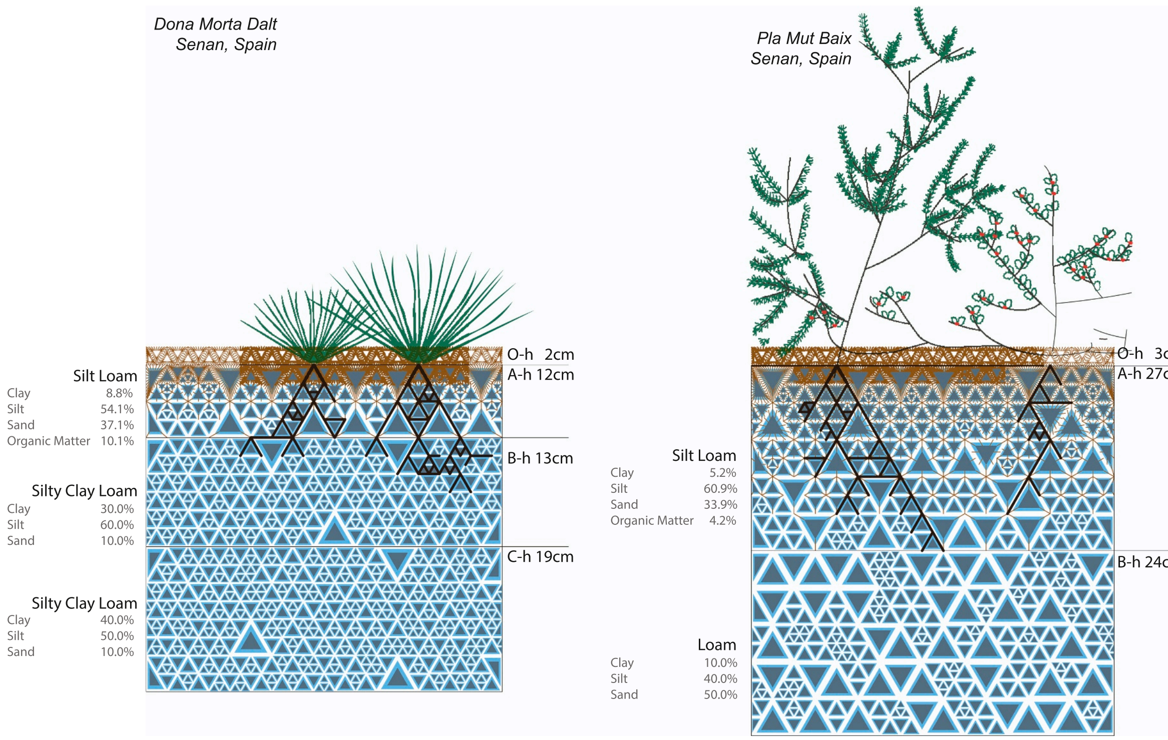

Fig. 12. Integrated and colored soil diagrams illustrating soil composition, water content, organic matter, and plant profiles from two sites in Senan, Spain. The diagrams are based on data gathered from local fieldwork surveys and laboratory analyses, offering a comprehensive visualization of the site-specific dynamics between soil properties and environmental factors.

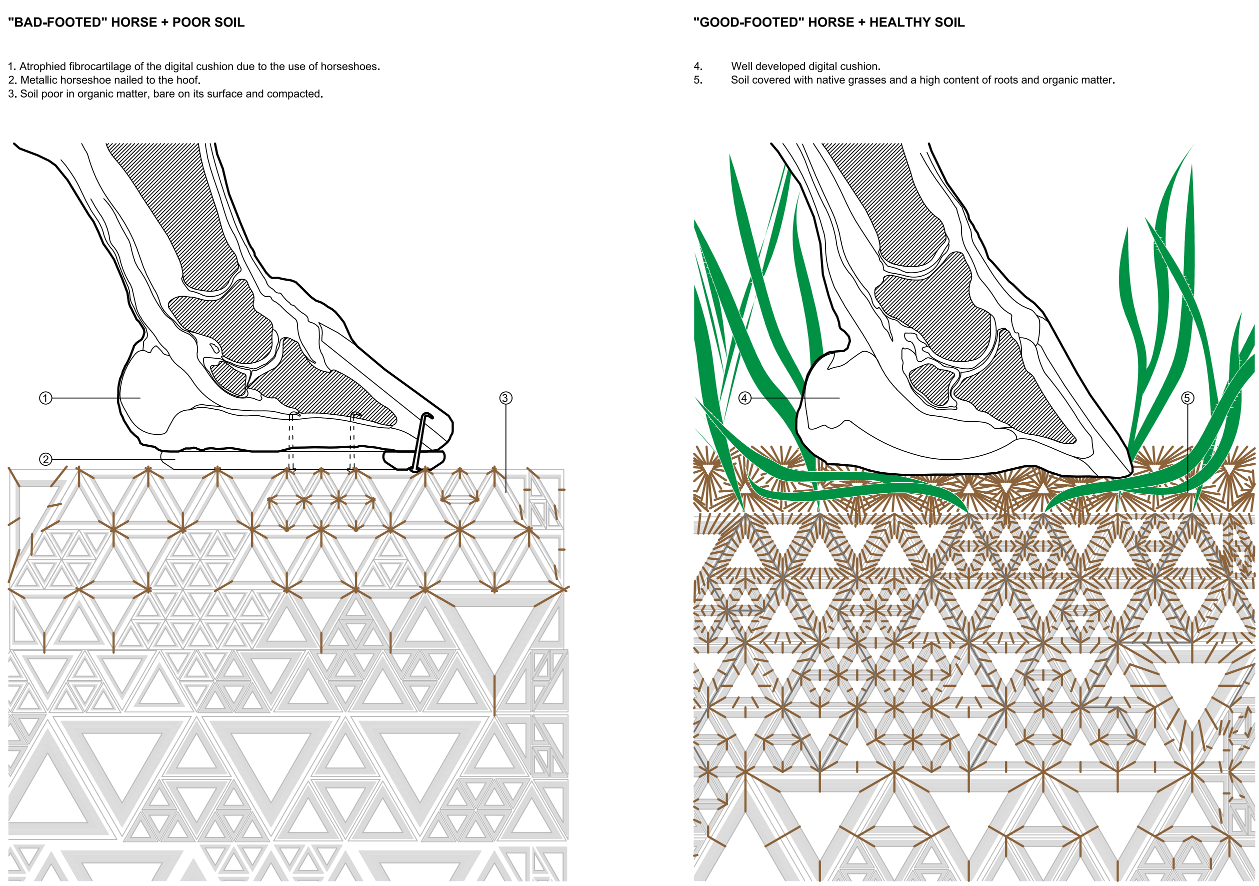

Fig. 13. Soil diagrams illustrating the effects of different soil conditions on horse feet, showcasing the impact of varying environmental factors on animal husbandry. Credit: Uxia Varela.

The paper also presents the critical algorithms for automating the diagram generation processes in detail and implements the entire system as a software plugin for the Rhino-Grasshopper CAD environment. This enables users to design and generate such visualizations parametrically. With the demonstrated usage of the *BeingAliveLanguage* in various real-world projects and our ongoing commitment and dedication, we will continue to develop the *BeingAliveLanguage* visualization system and explore additional extensions.

Code availability section

BeingAliveLanguage
Contact: ma@arch.ethz.ch.
Hardware requirements: x64 PC (Windows OS).
Program language: C#
Software required: Rhino 3D v7.0, Grasshopper v1.0 (shipped with Rhino 3D).
Program size: 1.6 M (this software only).
The source codes are available for downloading at the link: https://github.com/ChairBeingAlive/BeingAliveLanguageGH
The documentation of the software s available at the link: https://beingalivelanguage.arch.ethz.ch

CRediT authorship contribution statement

Zhao Ma: Methodology, Software, Writing-original-draft, Writing-review-editing. **Teresa Gali-Izard:** Conceptualization, Writing-review-editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to express their gratitude to Luke Harris, Cara Turett, Bonnie Kathleen Walker, and Uxia Varela for engaging in insightful discussions on the topics, as well as for their generous support and sharing of their previous work with the authors.

References

Aarthi, R., Sivakumar, D., 2020. An Enhanced Agricultural Data Mining Technique for Dynamic Soil Texture Prediction. Proc. Comput. Sci. 171, 2770–2778. https://doi.org/10.1016/j.procs.2020.04.301.

Alqadad, A., Shahrour, I., Sukik, A., 2017. Smart system for safe and optimal soil investigation in urban areas. Undergr. Space 2, 220–226. https://doi.org/10.1016/j.undsp.2017.10.003.

Andrade, R., Mancini, M., Teixeira, A.F.d.S., Silva, S.H.G., Weindorf, D.C., Chakraborty, S., Guilherme, L.R.G., Curi, N., 2022. Proximal sensor data fusion and auxiliary information for tropical soil property prediction: Soil texture. Geoderma 422, 115936. https://doi.org/10.1016/j.geoderma.2022.115936.

Araya, S., Ostendorf, B., Lyle, G., Lewis, M., 2018. CropPhenology: An R package for extracting crop phenology from time series remotely sensed vegetation index imagery. Ecol. Inform. 46, 45–56. https://doi.org/10.1016/j.ecoinf.2018.05.006.

Arrouays, D., Grundy, M.G., Hartemink, A.E., Hempel, J.W., Heuvelink, G.B.M., Hong, S. Y., Lagacherie, P., Lelyk, G., McBratney, A.B., McKenzie, N.J., Mendonca-Santos, M. d.L., Minasny, B., Montanarella, L., Odeh, I.O.A., Sanchez, P.A., Thompson, J.A., Zhang, G.L., 2014. Chapter Three - GlobalSoilMap: Toward a Fine-Resolution Global Grid of Soil Properties. In: Sparks, D.L. (Ed.), Advances in Agronomy, vol. 125. Academic Press, pp. 93–134. https://doi.org/10.1016/B978-0-12-800137-0.00003-0.

Bagnouls, F., Gaussen, H., 1957. Les climats biologiques et leur classification. Ann. Géogr. 66, 193–220. https://doi.org/10.3406/geo.1957.18273.

Ballabio, C., Panagos, P., Monatanarella, L., 2016. Mapping topsoil physical properties at European scale using the LUCAS database. Geoderma 261, 110–123. https://doi.org/10.1016/j.geoderma.2015.07.006.

Beaudette, D.E., Roudier, P., O'Geen, A.T., 2013. Algorithms for quantitative pedology: A toolkit for soil scientists. Comput. Geosci. 52, 258–268. https://doi.org/10.1016/j.cageo.2012.10.020.

Cicekci, O.C., Turkeri, M.K., Pekcan, O., 2014. Development of Soil Profile Visualization Software Using Game Engines, 3364–3372. doi: 10.1061/9780784413272.327.

Cope, M., Mikhailova, E., Post, C., Schlautman, M., McMillan, P., 2017. Developing an integrated cloud-based spatial-temporal system for monitoring phenology. Ecol. Inform. 39, 123–129. https://doi.org/10.1016/j.ecoinf.2017.04.007.

da Silva, A.L.B.R., Coolong, T., Diaz-Perez, J.C., 2019. Principles of irrigation and scheduling for vegetable crops in Georgia. UGA Coop. Ext. Bull 1511, 2–12.

Datta, S., Taghvaeian, S., Stivers, J., 2017. Understanding Soil Water Content and Thresholds For Irrigation Management. doi: 10.13140/RG.2.2.35535.89765.

Deval, C., Brooks, E.S., Dobre, M., Lew, R., Robichaud, P.R., Fowler, A., Boll, J., Easton, Z.M., Collick, A.S., 2022. Pi-VAT: A web-based visualization tool for decision support using spatially complex water quality model outputs. J. Hydrol. 607, 127529 https://doi.org/10.1016/j.jhydrol.2022.127529.

Filippi, O., 2007. Pour un jardin sans arrosage. ACTES SUD, Arles.

Filippucci, M., Rinchi, G., Brunori, A., Nasini, L., Regni, L., Proietti, P., 2016. Architectural modelling of an olive tree. Generative tools for the scientific visualization of morphology and radiation relationships. Ecol. Inform. 36, 84–93. https://doi.org/10.1016/j.ecoinf.2016.09.004.

Galí-Izard, T., Harris, L., Turett, C., Walker, B.K., 2022. A Conversation about Language. In: Designing Landscape Architectural Education. Routledge.

García-Gaines, R.A., Frankenstein, S., 2015. USCS and the USDA Soil Classification System: Development of a Mapping Scheme. REPORT. Cold Regions Research and Engineering Laboratory (U.S.).

Groenendyk, D.G., Ferré, T.P.A., Thorp, K.R., Rice, A.K., 2015. Hydrologic-Process-Based Soil Texture Classifications for Improved Visualization of Landscape Function. PLOS ONE 10, e0131299. https://doi.org/10.1371/journal.pone.0131299.

Hengl, T., de Jesus, J.M., Heuvelink, G.B.M., Gonzalez, M.R., Kilibarda, M., Blagotić, A., Shangguan, W., Wright, M.N., Geng, X., Bauer-Marschallinger, B., Guevara, M.A., Vargas, R., MacMillan, R.A., Batjes, N.H., Leenaars, J.G.B., Ribeiro, E., Wheeler, I., Mantel, S., Kempen, B., 2017. SoilGrids250m: Global gridded soil information based on machine learning. PLOS ONE 12, e0169748. https://doi.org/10.1371/journal.pone.0169748.

Hengl, T., de Jesus, J.M., MacMillan, R.A., Batjes, N.H., Heuvelink, G.B.M., Ribeiro, E., Samuel-Rosa, A., Kempen, B., Leenaars, J.G.B., Walsh, M.G., Gonzalez, M.R., 2014. SoilGrids1km — Global Soil Information Based on Automated Mapping. PLOS ONE 9, e105992. https://doi.org/10.1371/journal.pone.0105992.

Heung, B., Ho, H.C., Zhang, J., Knudby, A., Bulmer, C.E., Schmidt, M.G., 2016. An overview and comparison of machine-learning techniques for classification purposes in digital soil mapping. Geoderma 265, 62–77. https://doi.org/10.1016/j.geoderma.2015.11.014.

Hu, Z., Bass, B., Chan, C.W., Huang, G.H., 2004. An innovative approach for visualization of subsurface soil properties. Can. J. Soil Sci. 84, 63–70. https://doi.org/10.4141/S02-075.

Isikdogan, F., Bovik, A., Passalacqua, P., 2017. RivaMap: An automated river analysis and mapping engine. Remote Sens. Environ. 202, 88–97. https://doi.org/10.1016/j.rse.2017.03.044.

Jarray, N., Ben Abbes, A., Rhif, M., Dhaou, H., Ouessar, M., Farah, I.R., 2022. SMETool: A web-based tool for soil moisture estimation based on Eo-Learn framework and Machine Learning methods. Environ. Modell. Softw. 157, 105505 https://doi.org/10.1016/j.envsoft.2022.105505.

Jin, K., White, P.J., Whalley, W.R., Shen, J., Shi, L., 2017. Shaping an Optimal Soil by Root-Soil Interaction. Trends Plant Sci. 22, 823–829. https://doi.org/10.1016/j.tplants.2017.07.008.

Kuzyakov, Y., Blagodatskaya, E., 2015. Microbial hotspots and hot moments in soil: Concept & review. Soil Biol. Biochem. 83, 184–199. https://doi.org/10.1016/j.soilbio.2015.01.025.

McBratney, A.B., Mendonça Santos, M.L., Minasny, B., 2003. On digital soil mapping. Geoderma 117, 3–52. https://doi.org/10.1016/S0016-7061(03)00223-4.

McBratney, A.B., Odeh, I.O.A., Bishop, T.F.A., Dunbar, M.S., Shatar, T.M., 2000. An overview of pedometric techniques for use in soil survey. Geoderma 97, 293–327. https://doi.org/10.1016/S0016-7061(00)00043-4.

Menon, M., Robinson, B., Oswald, S.E., Kaestner, A., Abbaspour, K.C., Lehmann, E., Schulin, R., 2007. Visualization of root growth in heterogeneously contaminated soil using neutron radiography. Eur. J. Soil Sci. 58, 802–810. https://doi.org/10.1111/j.1365-2389.2006.00870.x.

Moradi, A.B., Carminati, A., Vetterlein, D., Vontobel, P., Lehmann, E., Weller, U., Hopmans, J.W., Vogel, H.J., Oswald, S.E., 2011. Three-dimensional visualization and quantification of water content in the rhizosphere. New Phytol. 192, 653–663. https://doi.org/10.1111/j.1469-8137.2011.03826.x.

Nguyen, T.V., Dietrich, J., Dang, T.D., Tran, D.A., Van Doan, B., Sarrazin, F.J., Abbaspour, K., Srinivasan, R., 2022. An interactive graphical interface tool for parameter calibration, sensitivity analysis, uncertainty analysis, and visualization for the Soil and Water Assessment Tool. Environ. Modell. Softw. 156, 105497 https://doi.org/10.1016/j.envsoft.2022.105497.

Nollenburg, M., Wolff, A., 2011. Drawing and Labeling High-Quality Metro Maps by Mixed-Integer Programming. IEEE Trans. Visual. Comput. Graph. 17, 626–641. https://doi.org/10.1109/TVCG.2010.81.

NRCS, USDA., 1993. Soil survey division staff (1993) soil survey manual. Soil conservation service. US Department of Agriculture Handbook 18, 315.

Oke, O., Siddiqui, S., 2015. Efficient automated schematic map drawing using multiobjective mixed integer programming. Comput. Oper. Res. 61, 1–17. https://doi.org/10.1016/j.cor.2015.02.010.

Pechanec, V., Brus, J., Kilianová, H., Machar, I., 2015. Decision support tool for the evaluation of landscapes. Ecol. Inform. 30, 305–308. https://doi.org/10.1016/j.ecoinf.2015.06.006.

Pohlmeier, A., Haber-Pohlmeier, S., Javaux, M., Vereecken, H., 2013. Magnetic Resonance Imaging Techniques for Visualization of Root Growth and Root Water Uptake Processes. In: Soil–Water–Root Processes: Advances in Tomography and Imaging. John Wiley & Sons, Ltd., pp. 137–156. https://doi.org/10.2136/sssaspecpub61.c7. Chapter 7.

Pourabdollah, A., Leibovici, D.G., Simms, D.M., Tempel, P., Hallett, S.H., Jackson, M.J., 2012. Towards a standard for soil and terrain data exchange: SoTerML. Comput. Geosci. 45, 270–283. https://doi.org/10.1016/j.cageo.2011.11.026.

Przewoźna, B., 2014. Changes of bulk density, air-water properties and morphology of soils in basins without outlets as an effect of erosion and anthropogenic denudation (a study from northwestern Poland). Soil Sci. Plant Nutr. 60, 30–37. https://doi.org/10.1080/00380768.2013.842456.

Qu, M., Li, W., Zhang, C., 2013. Assessing the spatial uncertainty in soil nitrogen mapping through stochastic simulations with categorical land use information. Ecol. Inform. 16, 1–9. https://doi.org/10.1016/j.ecoinf.2013.04.001.

Raunkiær, C., 1934. The Life Forms of Plants and Statistical Plant Geography. The Clarendon Press, Oxford.

Ritsema, C.J., Dekker, L.W., 2000. Preferential flow in water repellent sandy soils: Principles and modeling implications. J. Hydrol. 231–232, 308–319. https://doi.org/10.1016/S0022-1694(00)00203-1.

Robert, E.M., Schmitz, N., Copini, P., Gerkema, E., Vergeldt, F.J., Windt, C.W., Beeckman, H., Koedam, N., van As, H., 2014. Visualization of the stem water content of two genera with secondary phloem produced by successive cambia through Magnetic Resonance Imaging (MRI). J. Plant Hydraul., e0006 https://doi.org/10.20870/jph.2014.e006.

Samani, Z., 2000. Estimating Solar Radiation and Evapotranspiration Using Minimum Climatological Data. J. Irrig. Drain. Eng. 126, 265–267. https://doi.org/10.1061/(ASCE)0733-9437(2000)126:4(265).

Saxton, K.E., Rawls, W.J., 2006. Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. Soil Sci. Soc. Am. J. 70, 1569–1578. https://doi.org/10.2136/sssaj2005.0117.

Serrano-Notivoli, R., Longares, L.A., Cámara, R., 2022. Bioclim: An R package for bioclimatic classifications via adaptive water balance. Ecol. Inform. 71, 101810 https://doi.org/10.1016/j.ecoinf.2022.101810.

Specka, X., Gärtner, P., Hoffmann, C., Svoboda, N., Stecker, M., Einspanier, U., Senkler, K., Zoarder, M.A.M., Heinrich, U., 2019. The BonaRes metadata schema for geospatial soil-agricultural research data – Merging INSPIRE and DataCite metadata schemes. Comput. Geosci. 132, 33–41. https://doi.org/10.1016/j.cageo.2019.07.005.

Stott, J., Rodgers, P., Martínez-Ovando, J.C., Walker, S.G., 2011. Automatic Metro Map Layout Using Multicriteria Optimization. IEEE Trans. Visual. Comput. Graph. 17, 101–114. https://doi.org/10.1109/TVCG.2010.24.

Temme, A.J.A.M., Vanwalleghem, T., 2016. LORICA – A new model for linking landscape and soil profile evolution: Development and sensitivity analysis. Comput. Geosci. 90, 131–143. https://doi.org/10.1016/j.cageo.2015.08.004.

Villamil, M.B., Miguez, F.E., Bollero, G.A., 2008. Multivariate Analysis and Visualization of Soil Quality Data for No-Till Systems. J. Environ. Qual. 37, 2063–2069. https://doi.org/10.2134/jeq2007.0349.

Vogel, H.J., Eberhardt, E., Franko, U., Lang, B., Ließ, M., Weller, U., Wiesmeier, M., Wollschläger, U., 2019. Quantitative Evaluation of Soil Functions: Potential and State. Front. Environ. Sci. 7 https://doi.org/10.3389/fenvs.2019.00164.

Wanniarachchi, S., Sarukkalige, R., 2022. A Review on Evapotranspiration Estimation in Agricultural Water Management: Past, Present, and Future. Hydrology 9, 123. https://doi.org/10.3390/hydrology9070123.

Wiesmeier, M., Barthold, F., Blank, B., Kögel-Knabner, I., 2011. Digital mapping of soil organic matter stocks using Random Forest modeling in a semi-arid steppe ecosystem. Plant Soil 340, 7–24. https://doi.org/10.1007/s11104-010-0425-z.

Xu, Y., Chan, H.Y., Chen, A., 2022. Automated generation of concentric circles metro maps using mixed-integer optimization. Int. J. Geograph. Inf. Sci. 1–26. https://doi.org/10.1080/13658816.2022.2102636.

Yang, J., Shen, F., Wang, T., Wu, L., Li, Z., Li, N., Dai, L., Liang, J., Zhang, J., 2022. PEF-MODFLOW: A framework for preliminary soil profile horizon delineation based on soil color captured by smartphone images. Environ. Modell. Softw. 155, 105423 https://doi.org/10.1016/j.envsoft.2022.105423.

Yuan, Y., Li, B., Yu, W., Gao, X., 2021. Estimation and mapping of soil organic matter content at a national scale based on grid soil samples, a soil map and DEM data. Ecol. Inform. 66, 101487 https://doi.org/10.1016/j.ecoinf.2021.101487.

Zarebanadkouki, M., Kroener, E., Kaestner, A., Carminati, A., 2014. Visualization of Root Water Uptake: Quantification of Deuterated Water Transport in Roots Using Neutron Radiography and Numerical Modeling. Plant Physiol. 166, 487–499. https://doi.org/10.1104/pp.114.243212.

Zhang, C., Yang, Z., Zhao, H., Sun, Z., Di, L., Bindlish, R., Liu, P.W., Colliander, A., Mueller, R., Crow, W., Reichle, R.H., Bolten, J., Yueh, S.H., 2022. Crop-CASMA: A web geoprocessing and map service based architecture and implementation for serving soil moisture and crop vegetation condition data over U.S. Cropland. Int. J. Appl. Earth Obs. Geoinf. 112, 102902 https://doi.org/10.1016/j.jag.2022.102902.

Zhao, B., Li, Z., Li, P., Xu, G., Gao, H., Cheng, Y., Chang, E., Yuan, S., Zhang, Y., Feng, Z., 2017. Spatial distribution of soil organic carbon and its influencing factors under the condition of ecological construction in a hilly-gully watershed of the Loess Plateau, China. Geoderma 296, 10–17. https://doi.org/10.1016/j.geoderma.2017.02.010.