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The Megafauna3D Educational Environment: Harnessing the Combination of New and Traditional Technologies to Improve Geoscience Education and Outreach

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Abstract: The Megafauna3D project integrates advanced 3D scanning technologies and paleontological research to bring the extinct megafauna of Uruguay to formal and informal educational settings. Through the use of digitized fossil models, interactive education materials, and a web platform, the project engages the public and educational institutions in understanding the country's paleontological heritage. This manuscript presents Megafauna3D's multidisciplinary approach, its outreach initiatives, and the educational resources developed, such as 3D models and printed replicas, a book integrated with augmented reality, fanzines, and a teaching box. With a focus on open science, inclusivity, and accessibility, the project fosters public engagement with paleontological content and promotes fossil heritage conservation.

Keywords: quaternary; xenarthra; paleoecology; evolution; extinction

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1. Introduction

Paleontology has always captured the curiosity of people of all ages, mainly due to its capacity to show a deep past where the Earth was different from the planet we know today [1]. Yet, in Uruguay, the dissemination of paleontological knowledge has traditionally focused on taxa like dinosaurs (especially from regions outside South America), mostly owing to the availability of international resources and the lack of local initiatives. This focus has led to a gap in public awareness and understanding of the country's own fossil heritage, which is largely composed of many fossil groups of different geologic ages. In this context, despite their abundance in the Uruguayan fossil record, the long tradition in fossil collection and research, and the existence of specific outreach texts covering them [2], the giant mammals that once inhabited the region during the Late Pleistocene (~120,000–11,000 ka BP) continue to be seen in the popular culture as animals that inhabited northern continents. The megafauna of South America, including animals like giant ground sloths, glyptodonts, and saber-toothed cats, played a significant role in shaping ancient ecosystems, but their stories remain largely untold within Uruguay's educational and cultural landscape. Most textbooks and public discussions focus on foreign species, leaving the local paleontological wealth underappreciated.

At the same time, much of the available educational content in Uruguay about paleontology has traditionally been presented in an encyclopedic format, focusing on raw data and statistics. While informative, these approaches often lack the engaging, visual, and narrative elements needed to foster curiosity and a deeper understanding among students and the general public. Without visual and spatial references or interactive tools, local extinct fauna and paleontological sites tend to remain abstract and distant. Additionally,

many of Uruguay's museums with fossils, while holding valuable collections, are relatively unknown to the general public, contributing to a lack of connection with the country's rich paleontological history. In fact, many local museums house important historic collections, often dating back to the first half of the 20th century, while in other cases, fossils from Uruguay have been relevant pieces for science after being sent to European institutions by renowned scientists like Charles Darwin [3,4].

Recognizing these gaps, the Megafauna3D project (gestated at the Facultad de Ciencias, Universidad de la República and financed by the Agencia Nacional de Investigación e Innovación of Uruguay) was launched in 2015 as a groundbreaking project for Uruguay and South America, joining pioneering initiatives at the time such as the Smithsonian's 3D digitization program [5,6], the Florida Museum of Natural History [7], the Idaho Museum of Natural History's Virtual Museum initiative [8], and the GB3D Type Fossils Online project [9], aimed at bridging the divide between scientific research and public outreach. In this context, researchers have used digital 3D technologies for study and sharing fossil specimens for several years now, i.e., [10–12], but only more recently have these efforts been directed at educational and outreach settings, i.e., [13–15]. Most of these efforts have relied on new technologies that allow the obtainment of 3D data at relatively low costs (i.e., laser or structured light scanning and photogrammetry), while also making use of open, interactive, and web-based tools that allow improved accessibility to students and educators [16–19].

In tune with this, and leveraging new technologies such as 3D scanning, printing, and virtual reconstructions, Megafauna3D presents a novel way to engage with Uruguay's fossil record. The project focuses on the megafauna that roamed South America until the end of the Pleistocene (around 11,700 years ago), many of which have no modern analogs [20]. This initiative provides the public with unprecedented access to detailed 3D models of Uruguayan fossilized specimens of extinct species, allowing users to virtually explore these materials from their homes or classrooms. Moreover, Megafauna3D emphasizes the educational potential of these digital tools, developing activities and resources that make paleontological content accessible and exciting for learners of all ages.

In this contribution, we describe the project, its main products, and its current and potential uses as a valuable tool for the improvement of geosciences education and outreach, especially paleontology, both in formal and informal education settings.

2. Materials and Methods

2.1. Project Background

The Megafauna3D project is the result of a multidisciplinary collaboration between paleontologists, designers, developers, and educators, all of whom bring unique expertise to the project. The core of the team consists of researchers from the Facultad de Ciencias of the Universidad de la República in Montevideo, Uruguay, who have an extensive background in the study of large Pleistocene mammals. Their research, focused on the ecology [21–24], evolution [25–29], biogeography [30–33], and extinction [34,35] of these large mammals, forms the foundation of the project's scientific content. Furthermore, the team has pioneered the use of 3D technologies in paleontological research in Uruguay, employing these techniques to enhance both academic studies [36–41] and public outreach [42–44].

The team has been actively involved in fieldwork and research at significant fossil sites in Uruguay, such as the Arroyo del Vizcaíno (Adv), which has yielded a considerable number of fossils of Late Pleistocene megafauna [45,46]. The work at this and other locations has contributed valuable insights into different aspects of South American megafauna like ground sloths and glyptodonts, advancing understanding of how these animals interacted with their environment and the early human populations on the continent. In fact, the AdV site has provided evidence in favor of the early occupation of the region by humans, as early as ~35,000 ka BP [35,47–50]. The team's efforts in studying these fossils using tools like CT scans and photogrammetry, which have already fostered the production of open scientific data [51–53], are crucial to the simultaneous development of new and

enhanced educational and outreach materials and represents a scientific baseline for the Megafauna3D project.

2.2. Project Axes

The Megafauna3D project is built around several key axes that guide its development and implementation, each focusing on different aspects of the project's objective to connect paleontological research and public engagement. One of the core ideas behind the Megafauna3D project is the digitization of the fossil heritage of Uruguay as the base of the creation of an open platform of science education and outreach resources that can be used in both formal and informal educational settings. The project's materials are designed to be used by educators individually or as part of an integrated system, offering a modular approach that teachers, museum educators, or independent learners can adapt to specific needs and contexts. Another relevant aspect of the project is its multidisciplinary approach, merging scientific knowledge with technological tools, and artistic initiatives, ultimately creating a learning environment that combines active scientific learning with visually engaging and accessible content. Finally, the project aims to foster playfulness, imagination, and creativity as essential components of the learning process and to generate deeper connections to the country's natural heritage. A general flowchart of the project is depicted in Figure 1.

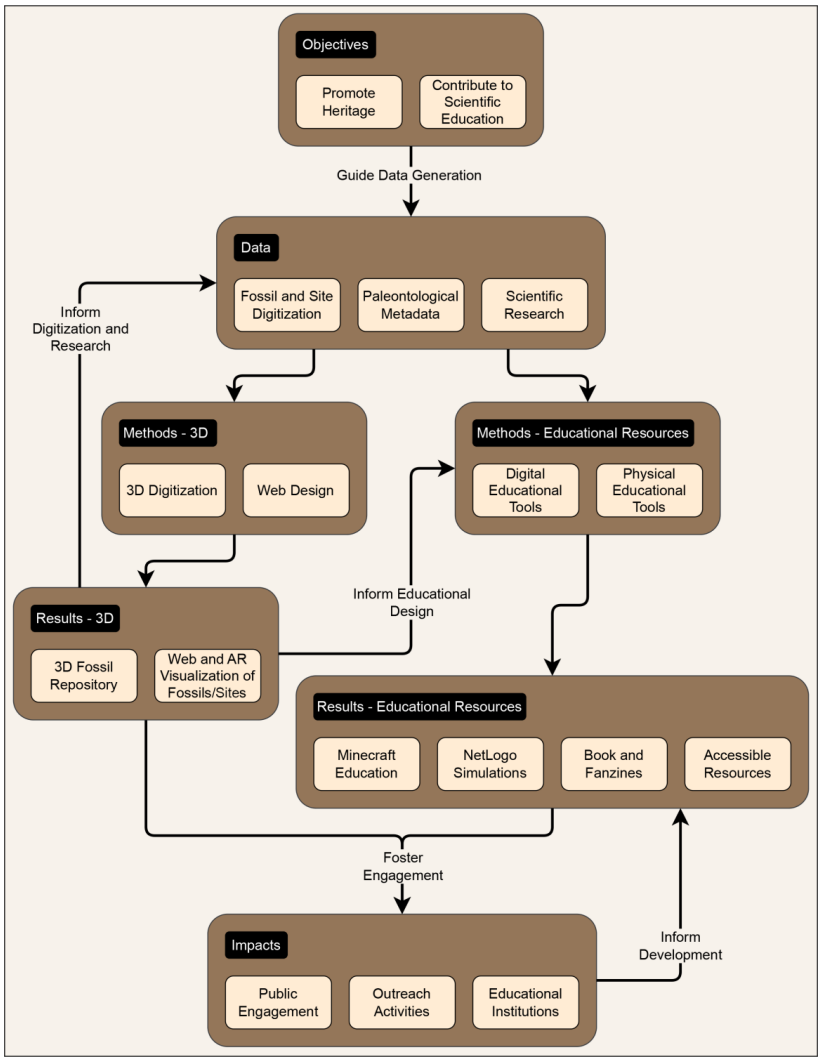

Figure 1. Flowchart depicting how the objectives, data acquisition, methods, results, and impacts are interconnected in the project.

2.3. Fossil Digitization Techniques

The project uses a range of advanced technologies to digitize fossil specimens, thus creating a digital archive that can be used for research, education, and outreach. One of the main techniques used is photogrammetry. This is a method that involves taking numerous (for optimal results, between 50 and 100, depending on the complexity of the object) high-resolution photographs of the relevant object from different angles (covering the entire object and maintaining a certain level of overlap between photographs), which are then submitted to specialized software (Agisoft Photoscan v.1.4.0; [54]) to align them and generate a 3D model. This technique allows for highly detailed and accurate reconstructions of fossil specimens using relatively portable equipment with the advantage that the computational part (the most time-consuming step) can be performed at the lab without the need to extend the time spent at collections. In addition to photogrammetry, a structured light scan (DAVID SLS-2) was used in some cases, which uses known patterns of light projected onto the relevant object to capture its surface's geometry in detail with an associated camera (Figure 2A,B). This method is particularly useful for capturing complex and small structures and surfaces in a short time. Although the required equipment is larger than that needed for photogrammetry, it is small enough to be portable and usable in common collection spaces. Finally, computed tomography (CT) scanning was also employed in the project. Computed tomography scanning is a technology traditionally used in medicine, but increasingly applied in the natural sciences and paleontology in particular. The main advantage of CT scans is the fact that they can capture the internal structure of the scanned objects, which is especially important for studying certain aspects of fossil specimens like the internal cavities of a skull. Regardless of the technique used, the fossil scans produced during the project ensure that the specimens are preserved in digital form and make them accessible for future research and educational purposes even if the original materials are lost or degraded over time (Figure 2C). Also, the availability of 3D models contributes to the prevention of fossil degradation by eliminating the need for manipulation and transport, while allowing for the model to be easily accessed remotely and simultaneously.

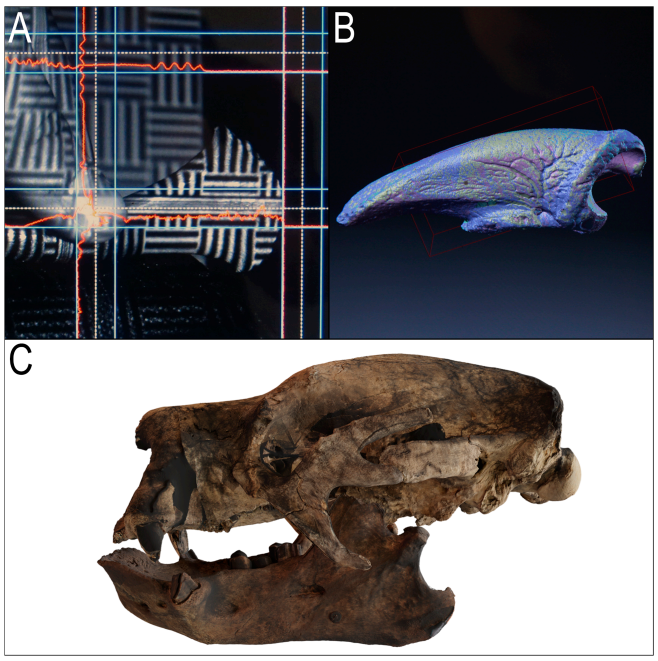

Figure 2. (**A**) Three-dimensional digitizing using the structured light method during the first step of surface acquisition. (**B**) Three-dimensional digitizing using the structured light method during surface alignment to complete the 3D model. (**C**) A render of the 3D model of a skull of the ground sloth *Lestodon armatus*.

2.4. Site Digitization

In addition to fossil digitization, the Megafauna 3D project has carried over the digitization of selected paleontological sites in Uruguay. The digital reconstructions of these sites allow users to virtually explore the landscapes where fossils are discovered and provide context to the fossilized specimens and the fieldwork carried out by scientists. In this context, the digitization of sites poses several challenges, such as the need to capture large-scale landscapes with high precision and the problems associated with working in outdoor environments where lighting and terrain can affect data collection. For this task, the standard pipeline used for the photogrammetry scans was complemented with the use of a drone (Mavic Pro) to perform aerial surveys and obtain aerial photographs that could be incorporated into the software [55]. Despite these challenges, the methodology allowed for the creation of detailed models that highlight the most important features of the sites, as well as the methodologies employed during scientific excavations.

2.5. Educational Material Design

2.5.1. Interactive Digital Tools

Once the fossils and sites were scanned and digitized, the data were processed using specialized software like Meshlab v.2023.12, 3D Slicer v.5.6.2, and Blender v.4.3.0 [56,57]. These tools were used to refine and clean the models, ensuring they are optimized for educational use and interactive platforms. The models were then uploaded to the Megafauna3D website, where users can view, manipulate, and explore them using a dedicated 3D viewer. For this, the website was developed using the open web application 3DHOP [58], which has been developed especially for use as an interactive platform focused on the showcasing of 3D digitized heritage. Before being uploaded, the models were converted to the Nexus format, a lightweight file format designed for web-based 3D visualization, which ensured that they can be accessed even in areas with limited internet bandwidth [59]. This focus on accessibility represents an important element of the project, ensuring that even schools and communities in remote and underserved areas can interact with the fossil models.

Augmented reality (AR) was implemented in different instances of the Megafauna3D project, enabling users to interact with 3D models of Pleistocene fossils in real-world settings. The AR activities were built as webapps using JavaScript libraries AR.js and MindAR.js, approaches that require no software installation and allow users to access AR experiences directly via a browser by scanning a QR code or marker. This method is optimized for low-resource devices, ensuring functionality on smartphones and tablets, even in areas with limited technology. Despite being lightweight, these libraries provide real-time rendering through WebGL, enabling users to rotate, zoom, and explore 3D models without compromising visual quality. The versatility of this approach has allowed the project to create experiences for different applications, including exhibitions, books, and outreach talks. This makes the AR experience accessible to educators and students, with no need for specialized hardware.

NetLogo models were implemented on the web platform to increase the educational use of the resources in formal educational settings. NetLogo is an agent-based modeling platform widely used to simulate complex systems in ecology and evolution, allowing users to model, for example, interactions like coevolution and predator–prey dynamics [60]. Its accessible coding language promotes computational thinking, making it suitable for students with no programming experience to modify and explore models [61]. NetLogo is commonly used in education to teach concepts by allowing students to experiment with simulations and observe outcomes in real time. In the Megafauna3D project, NetLogo is employed to simulate Pleistocene ecosystems, showcasing dynamics like predator–prey interactions, coevolution, and extinction cascades. In particular, a simulation was developed including a relatively complex ecosystem formed by two types of plants, two herbivores, and two carnivores to show how the extinction of one of the parts can have important repercussions on the equilibrium of other parts of the ecosystem and ultimately produce extinction cascades affecting species not directly associated with the extinct one.

Finally, a custom Minecraft Education Edition [62] world was developed to simulate a paleontological excavation in a local Uruguayan setting, making it relatable for students. This virtual world was designed to immerse students in a relatively realistic excavation scenario, where they explore a creek bed, uncover fossils of Pleistocene megafauna, and learn about Uruguay's ancient ecosystems. Using the tools available in Minecraft Education Edition, the world was populated with non-playable characters (NPCs) who provide guidance, scientific information, and links to further learning resources, thus merging with all the other resources developed in the Megafauna3D project. Interactive tools like cameras, notebooks, and shovels are provided to students by NPCs, allowing them to record their findings, take notes, and simulate the real processes paleontologists use in the field. The integration of these tools creates a dynamic, interactive environment where students can actively participate in uncovering fossils, documenting their discoveries, and learning key paleontological concepts through hands-on exploration, and then communicating the varied knowledge they acquired.

2.5.2. Physical Educational Resources

Beyond digital activities and resources, physical educational resources play an equally significant role in the project's outreach efforts. One major component is the production of 3D-printed fossil replicas, which allow students and educators to physically interact with accurate versions of fossils such as glyptodon plates or saber-toothed cat teeth. These replicas are used in classrooms and exhibitions, giving learners a tactile experience that enhances their understanding of the size, texture, and structure of these ancient animals. The availability of these physical models provides an essential hands-on learning tool that complements digital materials, making paleontology more tangible and relatable.

In addition to fossil digitization, the artistic representation of megafauna plays a crucial role in the Megafauna3D project. Paleoartists collaborate closely with paleontologists to create scientifically accurate yet visually compelling depictions of extinct animals. These artists use the 3D models as a foundation, combining them with fossil evidence to reconstruct the appearance and behavior of the species. The result is a rich collection of paleoart, digital illustrations, and manual drawings, all integrated into printed educational materials that bring the megafauna to life for modern audiences. This collaboration ensures the representations maintain anatomical rigor while leaving room for imagination and speculation, particularly in areas where fossil evidence is incomplete. This balance between science and creativity is crucial to the project's goal of making paleontology engaging and accessible to a broad audience.

The project also incorporates printed educational resources, such as fanzines, books, and open manuals for both students and teachers. The fanzines, filled with illustrations and simplified scientific explanations, are particularly targeted at younger audiences, offering an approachable and low-cost introduction to Uruguay's megafauna. These printed materials serve as standalone educational tools or as companions to the 3D models and digital platforms, ensuring that learners of different ages and learning styles can engage with the content. In addition, manuals and guides have been developed to help educators integrate these resources into their lessons, providing structured activities and comprehensive instructions to maximize their impact in the classroom. These activities delve into the morphological, ecological, and evolutionary characteristics of the species, fostering the inclusion of critical and scientific thought to learn about the similarities and differences among the members of the extinct megafauna, as well as with extant native fauna in the country.

Finally, further expanding on the project's commitment to open materials and accessibility, Megafauna3D collaborated with other institutions to start to develop inclusive materials, such as Braille texts, scale figures of Pleistocene megafauna, and sign language videos, ensuring that students with visual or hearing impairments can participate fully in the learning process. A dedicated educational box kit has also been designed, containing a curated selection of physical resources, including 3D-printed replicas, educational post-

cards, and activity guides. These kits were distributed to schools and museums, particularly in rural areas, during a series of talks and workshops designed to promote the project and its use in educational institutions. This holistic approach ensures that the project not only delivers cutting-edge digital tools but also provides physical, accessible resources that cater to diverse learning environments and needs.

3. Results and Discussion

3.1. Digitized Fossil Database

The digitization campaign covered eight institutions housing fossil collections in Uruguay, namely Museo Nacional de Historia Natural, Museo de Historia Natural Dr. Carlos A. Torres de la Llosa, and Facultad de Ciencias, Universidad de la República from Montevideo; Colección Paleontológica del Arroyo del Vizcaíno from Canelones; Museo Paleontológico Armando Calcaterra and Museo Municipal de Colonia Dr. Bautista Rebuffo from Colonia; Museo Paleontológico de Dolores from Soriano; Museo Arqueológico de Río Negro from Río Negro; and Museo de Arqueología y Ciencias Naturales from Salto. Also, several fossils housed at educational institutions like primary and secondary schools were digitized and added to the database. A total of 71 fossil specimens, which represent both predators and herbivores from the Late Pleistocene of the country, were scanned. The taxa covered by the database are: the sloths *Lestodon armatus*, *Glossotherium robustum*, *Mylodon darwini*, *Valgipes bucklandi*, and *Nothrotheriops* sp.; the glyptodonts *Glyptodon reticulatus*, *Panochthus tuberculatus*, and *Doedicurus clavicaudatus*; the equid *Hippidion principale*; the proboscidean *Notiomastodon platensis*; the toxodontid *Toxodon platensis*; the ursid *Arctotherium* sp.; and the felid *Smilodon populator*. The models were captured with different techniques and originally in different formats, but all models were standardized to the STL format, a widely used format that is compatible with almost all open-source software, and the Nexus format to be implemented on the web platform. The database has recently been uploaded to the open repository MorphoSource to be made available to researchers for morphometric studies, biomechanical analyses, and evolutionary comparisons, as well as to educators wanting to teach students about these animals and their fossils. Overall, the digitization has ensured the preservation of the fossils and enabled their open dissemination, promoting both scientific study and educational outreach.

3.2. Online Platform

The main product of the Megafauna 3D project is the online platform, which serves as the central hub for accessing digitized fossil collections and associated educational materials (Figure 3A). At its core is a 3D fossil gallery filtered by species in which users can explore all the related 3D models of the fossil specimens, covering several different elements of the skeletons and including the ability to rotate, zoom, and examine the models in the interactive 3D viewer. Each model is accompanied by its metadata, accessible from a tab alongside the interactive viewer, that includes information such as species and skeleton element, discovery location, scan technique, institution where the specimen is housed, collector, assigned age, and catalog number. The platform is designed for intuitive navigation, ensuring accessibility for users of all ages and technical abilities, and is fully compatible with touch screens. Additional features include interactive educational activities, such as comparing species' teeth or skulls, which engage users in understanding the functional morphology of these extinct animals. Also, anaglyph videos of fossils selected for their didactic potential were created to be viewed with 3D glasses, which can be manufactured by students using a free template downloadable from the platform.

Moreover, the project has successfully expanded its initial objective to scan specimens to also include paleontological sites of Uruguay. Virtual visits make use of the online Sketchfab platform, allowing for the generation of key interest points that include information and images alongside an interactive path of the site, allowing users to explore excavation processes, stratigraphy, and fossil distribution across landscapes (Figure 3C). The initiative not only enhances educational content but also preserves significant paleontological data

for future research, contributing to making the platform a comprehensive digital repository for paleontological learning.

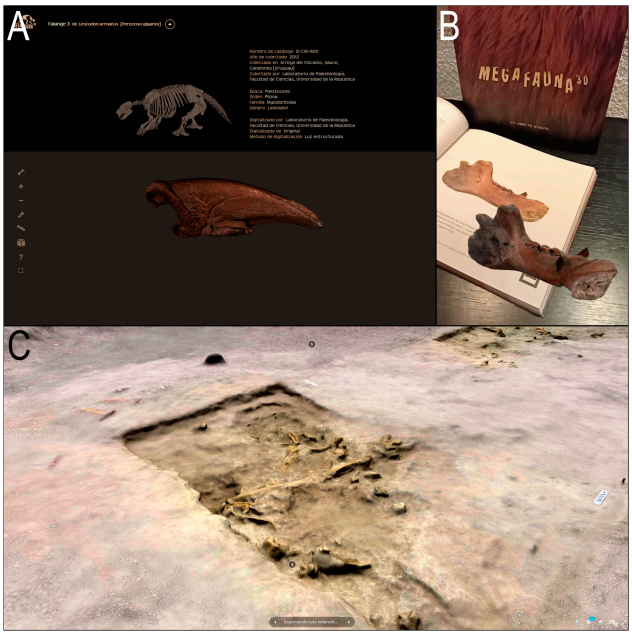

Figure 3. (**A**) Web platform at megafauna3d.org (accessed on 19 November 2024) showing 3D model metadata (including physical object data) and the interactive visualizer. (**B**) Augmented reality incorporated in the Megafauna3D book, running as a web-app without the need to install specific software. (**C**) Virtual visit to a fossil excavation site in Uruguay developed in Sketchfab, including interest points and site information.

3.3. Augmented Reality

Augmented reality (AR) integration was developed as a standout feature of the Megafauna3D project and has been incorporated into educational materials and public exhibitions to offer immersive experiences. The resulting implementations allow users to interact with life-size 3D models of extinct megafauna by seamlessly scanning images or QR codes with their smartphones or tablets, without needing high-end devices or software installations. The webapp-based AR approach ensures that even users in areas with limited resources or connectivity can access the experience. In this context, the AR features have been integrated into the project's outreach book, as well as into a small exhibition at the Arroyo del Vizcaíno site, in which the animals can be experienced in real-life sizes by visitors, creating a multi-sensory experience for learners (Figure 3B).

3.4. NetLogo Models and Minecraft World

The project employs NetLogo for simulating ecological and evolutionary processes, allowing students to visualize predator–prey dynamics, population changes, and extinction cascades within Pleistocene ecosystems. These interactive models encourage computational thinking, as students can manipulate variables like the environment or species population to observe the effects on ecosystems. The simulations are designed to engage students in problem-solving, offering a hands-on approach to understanding complex systems. NetLogo's flexibility allows users to modify models, making it a valuable tool for exploring both past ecosystems and contemporary environmental challenges like biodiversity loss. These activities have been implemented on the NetLogo Web platform, making them totally open and accessible for any device, further contributing to the goal of making all resources completely open and accessible to students and educators (Figure 4C).

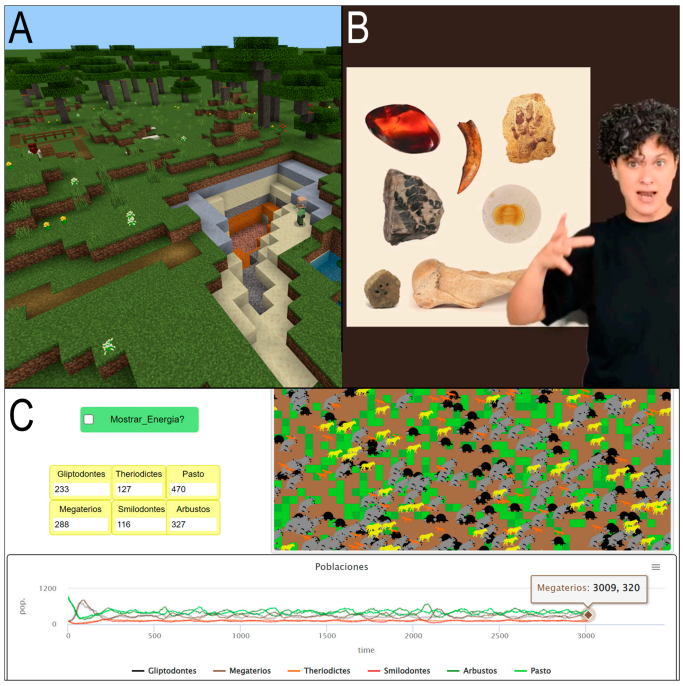

Figure 4. (**A**) Minecraft Education world developed for use alongside the other educational resources in primary school settings. (**B**) Sign language videos focused on increasing the accessibility of the project. (**C**) NetLogo web agent-based model simulating a Late Pleistocene ecosystem with different species and their interactions, showing ecosystem stability and the impact of different perturbations and extinction cascades.

In addition, the project developed a Minecraft world that simulates paleontological excavations of Uruguay's Late Pleistocene megafauna (Figure 4A). Built using Minecraft Education Edition, this world immerses students in the role of paleontologists, where they dig for fossils, document findings, and analyze ancient ecosystems, all while depicting a local recognizable setting in Uruguay. Non-playable characters (NPCs), created with the aim of making them relatable to students and avoiding stereotypes associated with scientists, guide students through the excavation process, providing information on fossilization and the environmental factors that contributed to species extinction. These NPCs represent different people involved in an excavation site, such as teachers, neighbors, students, researchers, and paleontologists. The Minecraft world promotes teamwork, hypothesis testing, and data collection skills, mimicking real-world paleontological research while engaging students in a fun, educational activity. The initiative was made possible by the collaboration with Ceibal (Conectividad Educativa de Informática Básica para el Aprendizaje en Línea), an agency of the Uruguayan government that promotes educational innovations using digital technologies, which provided licenses and has the capacity to reach all Uruguayan primary schools through its connectivity and device network [63].

3.5. Integration of Digital Resources with Printed Educational Resources

The Megafauna3D project integrates its digital and physical resources to create a comprehensive educational ecosystem in which both scientific knowledge and artistic representations coexist (Figure 5A,B). One notable example is the project's book, which combines traditional text with augmented reality (AR) to provide a unique interactive learning experience (Figure 5D). In addition to the book, the project produced fanzines and open manuals for teachers and students, which offer engaging visual content and structured lesson plans that are combined with the digital resources through QR codes (Figure 5C). The inclusion of 3D-printed fossil replicas further bridges the gap between the digital and physical worlds, giving students a hands-on way to explore fossils. The blend of digital and printed media makes learning more immersive and provides a deeper understanding

of the subject matter, while the physical tools combined with the digital platform enable educators to provide a multifaceted learning experience that appeals to various learning styles and needs. In this context, an education box was developed combining all these resources, making it an educational kit that represents a self-contained paleontological learning experience that can be deployed in varied educational contexts (Figure 6A). The box was distributed for free to different educational and heritage conserving institutions and can be easily scaled up to gradually expand its presence in the educational landscape of Uruguay.

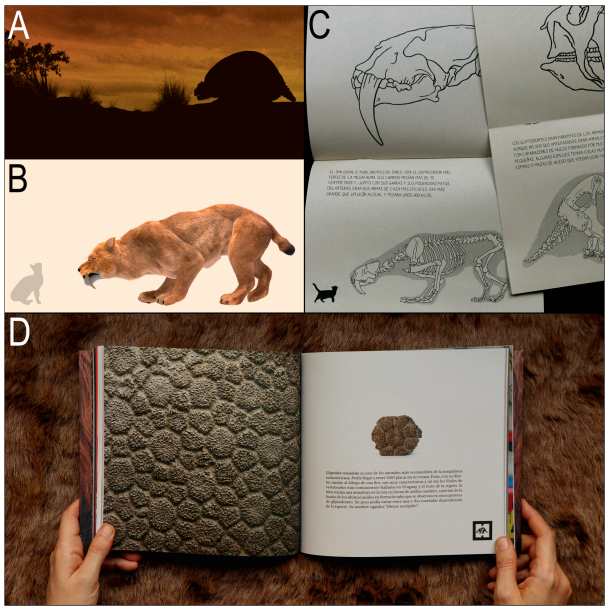

Figure 5. (**A**,**B**) Paleoartistic representations of the Late Pleistocene megafauna of Uruguay. (**C**) Fanzines developed during the project and openly distributed via the Megafauna3D website. (**D**) The physical book "Megafauna3D: un libro de huesos", merging traditional media with new technologies.

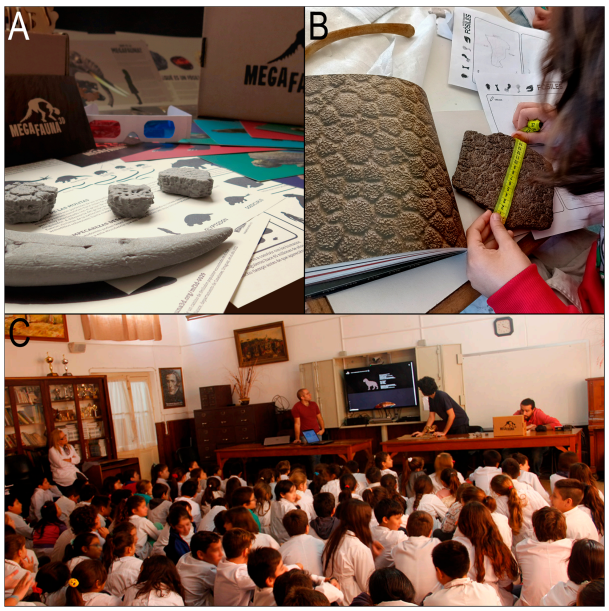

Figure 6. (**A**) The educational kit developed for the Megafauna3D project. (**B**) An active learning workshop with primary school children in the context of the science outreach activities carried out during the project. (**C**) The presentation of the project and its educational resources at a public school in Uruguay.

3.6. Accessible Resources

Finally, the most recent objective of the project has been to incorporate new ways and tools to ensure accessibility for all learners, including those with disabilities. In this context, the project has fostered collaboration with local specialized institutions like the Centro de Desarrollo Accesible (CERESO) and Centro de Recursos para Estudiantes con Discapacidad Visual (CER), both part of the National Public Educational Administration (ANEP), to develop educational materials for students with visual and hearing impairments. Although still in its preliminary stages, some resources have already been produced, including Braille texts, tactile replicas, audio descriptions, accessible pdf manuals and educator's guides, and sign language videos explaining key concepts related to ecology, evolution, and extinction (Figure 4B).

4. Making an Educational and Outreach Environment

From its creation as an online gallery of 3D models of fossil bones to its current form, the Megafauna3D project has become a comprehensive dissemination environment, designed to share Uruguay's paleontological heritage with the widest possible audience. This environment is built upon a diverse array of resources and tools that engage users through multiple platforms, both digital and physical. The project's goal is to create an interconnected system where each component (whether it be a 3D model, educational booklet, augmented reality experience, or a physical portable exhibit) functions independently but can also interact with other elements to provide a richer, more cohesive educational experience (Figure 6B,C). By embracing a multi-platform approach, Megafauna3D ensures that its resources are accessible in different contexts, from schools and museums to home learning environments.

This environment of dissemination also prioritizes flexibility and inclusivity. The project's tools are designed to be used across a variety of settings, from rural schools with limited access to technology to advanced museum exhibitions in urban centers. The incorporation of both high-tech elements, like interactive online platforms and 3D-printed replicas, and low-tech materials, like printed fanzines and AR webapps that function on low-resource mobile cell phones, ensures that the project can reach diverse audiences. Furthermore, the environment promotes active learning, encouraging participants to not only consume information but to interact with and explore the world of the megafauna through virtual visits, simulations, and game contexts. This dynamic, user-centered approach transforms paleontology from a static discipline into an engaging, participatory experience.

5. Conclusions and Perspectives

The Megafauna3D project has successfully bridged the gap between scientific research, education, and public outreach, providing an innovative approach to paleontology in Uruguay. Since its inception, the project has achieved several key milestones, including the digitization of significant Pleistocene fossils, the development of interactive educational tools, and the integration of 3D modeling and augmented reality into formal and informal educational settings. By collaborating with schools, museums, and researchers, Megafauna3D has brought Uruguay's paleontological heritage more reachable, allowing students and the general public to explore the country's extinct megafauna in new and engaging ways. The creation of accessible content has further promoted a broader understanding and appreciation of paleontology.

From its launch, the website has received more than 67,000 visits, mainly from Uruguay (~25,000 visits) and Argentina, the United States, Mexico, Brazil, Spain, Chile, Colombia, and Peru, showing how the project has impacted Spanish speaking countries and the region. Within Uruguay, the website is frequently visited from every administrative division (department) of the country, resulting in an average of ~800 visits per month. Furthermore, the presence across social networks, including communications about outreach activities and digital resources, has generated over 4500 followers on X, Instagram, and Facebook combined. This approach has significantly increased the number of people participating

in outreach events carried out at the AdV fossil collection, often receiving more than 500 persons during events like the National Heritage Day or Night of the Museums. Similarly, the number of in-person activities and talks in primary and secondary education institutions has increased, reaching institutions in almost all departments.

Looking ahead, the project envisions scaling its efforts to create more inclusive educational resources for impaired students, ensuring that Braille texts, sign language videos, and tactile fossil replicas are widely available across Uruguay. Expanding the use of Megafauna3D's resources in different regions of the country remains a priority, and collaborations with rural schools and institutions will be crucial for that. Additionally, the increase in digitized fossil specimens and sites and their availability in the online platform will be important for the expansion of the project and the broadening of access to the country's paleontological heritage. The combination of these efforts will allow Megafauna3D to continue offering an attractive and innovative approach to geosciences outreach and education.

Ultimately, Megafauna3D demonstrates how new technologies can transform the way geosciences are taught and appreciated, while also serving as a powerful tool for the conservation and valorization of natural heritage. The continued integration of cutting-edge tools with more traditional approaches will be crucial for preserving fossils, as well as fostering a deeper connection between society and natural heritage.

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References

1. Forli, M.; Guerrini, A. *The History of Fossils Over Centuries: From Folklore to Science*; Springer: Berlin/Heidelberg, Germany, 2022.
2. Fariña, R.A.; Vizcaíno, S.F. *Hace Sólo 10.000 Años*; Fin de Siglo: Montevideo, Uruguay, 1995.
3. Fernicola, J.C.; Vizcaíno, S.F.; De Iuliis, G. The fossil mammals collected by Charles Darwin in South America during his travels on board the HMS Beagle. *Rev. De La Asoc. Geológica Argent.* **2009**, *64*, 147–159.
4. Vizcaíno, S.F.; Fariña, R.A.; Fernicola, J.C. Young Darwin and the ecology and extinction of Pleistocene South American fossil mammals. *Rev. De La Asoc. Geológica Argent.* **2009**, *64*, 160–169.
5. Hollinger, R.E.; John Jr, E.; Jacobs, H.; Moran-Collins, L.; Thome, C.; Zastrow, J.; Metallo, A.; Waibel, G.; Rossi, V. Tlingit-Smithsonian collaborations with 3D digitization of cultural objects. *Mus. Anthropol. Rev.* **2013**, *7*, 201–253.
6. Metallo, A.; Rossi, V. The future of three-dimensional imaging and museum applications. *Curator Mus. J.* **2011**, *54*, 63–69. [CrossRef]

7. Ziegler, M.J.; Perez, V.J.; Pirlo, J.; Narducci, R.E.; Moran, S.M.; Selba, M.C.; Hastings, A.K.; Vargas-Vergara, C.; Antonenko, P.D.; MacFadden, B.J. Applications of 3D paleontological data at the Florida Museum of Natural History. *Front. Earth Sci.* **2020**, *8*, 600696. [CrossRef]
8. Maschner, H.D.; Schou, C.D.; Holmes, J. Virtualization and the democratization of science: 3D technologies revolutionize museum research and access. In Proceedings of the 2013 Digital Heritage International Congress (DigitalHeritage), Marseille, France, 28 October–1 November 2013; IEEE: New York, NY, USA, 2013; Volume 2; pp. 265–271.
9. McCormick, T.; Howe, M.P. The GB/3D Type Fossils Online Web Portal. In *AGU Fall Meeting Abstracts*; American Geophysical Union: San Francisco, CA, USA, 9–13 December 2013; Volume 2013; p. ED14C-01.
10. Tafforeau, P.; Boistel, R.; Boller, E.; Bravin, A.; Brunet, M.; Chaimanee, Y.; Cloetens, P.; Feist, M.; Hoszowska, J.; Zabler, S.; et al. Applications of X-ray synchrotron microtomography for non-destructive 3D studies of paleontological specimens. *Appl. Phys. A* **2006**, *83*, 195–202. [CrossRef]
11. Sutton, M.D. Tomographic techniques for the study of exceptionally preserved fossils. *Proc. R. Soc. B Biol. Sci.* **2008**, *275*, 1587–1593. [CrossRef]
12. Niven, L.; Steele, T.E.; Finke, H.; Gernat, T.; Hublin, J.J. Virtual skeletons: Using a structured light scanner to create a 3D faunal comparative collection. *J. Archaeol. Sci.* **2009**, *36*, 2018–2023. [CrossRef]
13. Lee EA, L.; Wong, K.W. Learning with desktop virtual reality: Low spatial ability learners are more positively affected. *Comput. Educ.* **2014**, *79*, 49–58. [CrossRef]
14. Neumüller, M.; Reichinger, A.; Rist, F.; Kern, C. 3D printing for cultural heritage: Preservation, accessibility, research and education. In *3D Research Challenges in Cultural Heritage: A Roadmap in Digital Heritage Preservation*; Ioannides, M., Quak, E., Eds.; Springer International Publishing: Cham, Switzerland, 2014; pp. 119–134.
15. Grant, C.; Antonenko, P.; Wood, A.; MacFadden, B. 3D Scanning of Fossils for Middle and High School Students: Science Teachers and Students' Perspectives. *Res. Highlights Technol. Teach. Educ.* **2015**, *2015*, 97.
16. Rahman, I.A.; Adcock, K.; Garwood, R.J. Virtual fossils: A new resource for science communication in paleontology. *Evol. Educ. Outreach* **2012**, *5*, 635–641. [CrossRef]
17. Lebrun, R.; Orliac, M.J. MorphoMuseuM: An online platform for publication and storage of virtual specimens. *Paleontol. Soc. Pap.* **2016**, *22*, 183–195. [CrossRef]
18. Cárdaba, J.A.; Presumido, M.; Fesharaki, O.; Martín-Perea, D.M.; Prieto, I. Dissemination Of Paleontological Heritage Through The Use Of New Technologies: The Example Of The Somosaguas Site (Madrid, Spain). In Proceedings of the INTED2018, Valencia, Spain, 5–7 March 2018; pp. 488–496.
19. Cunningham, J.A. The use of photogrammetric fossil models in palaeontology education. *Evol. Educ. Outreach* **2021**, *14*, 1. [CrossRef]
20. Fariña, R.A.; Vizcaíno, S.F.; De Iuliis, G. *Megafauna: Giant Beasts of Pleistocene South America*; Indiana University Press: Bloomington, IN, USA, 2013.
21. Varela, L.; Fariña, R.A. Masseter moment arm as a dietary proxy in herbivorous ungulates. *J. Zool.* **2015**, *296*, 295–304. [CrossRef]
22. Fariña, R.A.; Varela, L. Comment on "Isotopic insight on paleodiet of extinct Pleistocene megafaunal Xenarthrans from Argentina" by H. Bocherens, M. Cotte, RA Bonini, P. Straccia, D. Scian, L. Soibelzon and FJ Prevosti, Gondwana Research, Volume 48, Issue 1, Pages 7–14. *Gondwana Res.* **2021**, *58*, 241–242. [CrossRef]
23. Varela, L.; Clavijo, L.; Tambusso, P.S.; Fariña, R.A. A window into a late Pleistocene megafauna community: Stable isotopes show niche partitioning among herbivorous taxa at the Arroyo del Vizcaíno site (Uruguay). *Quat. Sci. Rev.* **2023**, *317*, 108286. [CrossRef]
24. Varela, L.; Tambusso, S.; Fariña, R. Femora nutrient foramina and aerobic capacity in giant extinct xenarthrans. *PeerJ* **2024**, *12*, e17815. [CrossRef] [PubMed]
25. Buckley, M.; Fariña, R.A.; Lawless, C.; Tambusso, P.S.; Varela, L.; Carlini, A.A.; Powell, J.E.; Martinez, J.G. Collagen sequence analysis of the extinct giant ground sloths Lestodon and Megatherium. *PLoS ONE* **2015**, *10*, e0139611.
26. Varela, L.; Tambusso, P.S.; McDonald, H.G.; Fariña, R.A. Phylogeny, macroevolutionary trends and historical biogeography of sloths: Insights from a Bayesian morphological clock analysis. *Syst. Biol.* **2019**, *68*, 204–218. [CrossRef]
27. Varela, L.; Tambusso, P.S.; Fariña, R. Unexpected inhibitory cascade in the molariforms of sloths (Folivora, Xenarthra): A case study in xenarthrans honouring Gerhard Storch's open-mindedness. *Foss. Impr.* **2020**, *76*, 1–16. [CrossRef]
28. Varela, L.; McDonald, H.G.; Fariña, R. Sexual dimorphism in the fossil ground sloth Lestodon armatus (Xenarthra, Folivora). *Hist. Biol.* **2022**, *34*, 525–537. [CrossRef]
29. Baleka, S.; Varela, L.; Tambusso, P.S.; Paijmans, J.L.; Mothé, D.; Stafford, T.W.; Fariña, R.A.; Hofreiter, M. Revisiting proboscidean phylogeny and evolution through total evidence and palaeogenetic analyses including Notiomastodon ancient DNA. *Iscience* **2022**, *25*, 103559. [CrossRef] [PubMed]
30. Varela, L.; Fariña, R.A. Co-occurrence of mylodontid sloths and insights on their potential distributions during the late Pleistocene. *Quat. Res.* **2016**, *85*, 66–74. [CrossRef]
31. Varela, L.; Tambusso, P.S.; Patiño, S.J.; Di Giacomo, M.; Fariña, R.A. Potential distribution of fossil xenarthrans in South America during the late Pleistocene: Co-occurrence and provincialism. *J. Mamm. Evol.* **2018**, *25*, 539–550. [CrossRef]
32. Varela, L.; Tambusso, P.S.; McDonald, H.G.; Vezzosi, R.I.; Fariña, R.A. Occurrence of the ground sloth Nothrotheriops (Xenarthra, Folivora) in the Late Pleistocene of Uruguay: New information on its dietary and habitat preferences based on stable isotope analysis. *J. Mamm. Evol.* **2023**, *30*, 561–576. [CrossRef]

33. Lobato, C.; Varela, L.; Tambusso, P.S.; Miño-Boilini, Á.R.; Clavijo, L.; Fariña, R.A. Presence of the ground sloth Valgipes bucklandi (Xenarthra, Folivora, Scelidotheriinae) in southern Uruguay during the Late Pleistocene: Ecological and biogeographical implications. *Quat. Int.* **2021**, *601*, 104–115. [CrossRef]
34. Fariña, R.A. Bone surface modifications, reasonable certainty, and human antiquity in the Americas: The case of the Arroyo Del Vizcaíno Site. *Am. Antiq.* **2015**, *80*, 193–200. [CrossRef]
35. Domínguez-Rodrigo, M.; Baquedano, E.; Varela, L.; Tambusso, P.S.; Melián, M.J.; Fariña, R.A. Deep classification of cut-marks on bones from Arroyo del Vizcaíno (Uruguay). *Proc. R. Soc. B* **2021**, *288*, 20210711. [CrossRef]
36. Tambusso, P.S.; Fariña, R.A. Digital cranial endocast of *Pseudoplohophorus absolutus* (Xenarthra, Cingulata) and its systematic and evolutionary implications. *J. Vertebr. Paleontol.* **2015**, *35*, e967853. [CrossRef]
37. Tambusso, P.S.; Fariña, R.A. Digital endocranial cast of *Pampatherium humboldtii* (Xenarthra, Cingulata) from the Late Pleistocene of Uruguay. *Swiss J. Palaeontol.* **2015**, *134*, 109–116. [CrossRef]
38. Tambusso, P.S.; Varela, L.; Góis, F.; Moura, J.F.; Villa, C.; Fariña, R.A. The inner ear anatomy of glyptodonts and pampatheres (Xenarthra, Cingulata): Functional and phylogenetic implications. *J. S. Am. Earth Sci.* **2021**, *108*, 103189. [CrossRef]
39. Tambusso, P.S.; Góis, F.; Moura, J.F.; Villa, C.; do Amaral, R.V. Paleoneurology of extinct cingulates and insights into their inner ear anatomy. In *Paleoneurology of Amniotes: New Directions in the Study of Fossil Endocasts*; Springer International Publishing: Cham, Switzerland, 2023; pp. 711–736.
40. Patiño, S.; Perez Zerpa, J.; Fariña, R.A. Finite element and morphological analysis in extant mammals' claws and quaternary sloths' ungual phalanges. *Hist. Biol.* **2021**, *33*, 857–867. [CrossRef]
41. Varela, L.; Tambusso, P.S.; Zerpa, J.M.P.; McAfee, R.K.; Fariña, R.A. 3D finite element analysis and geometric morphometrics of sloths (Xenarthra, Folivora) mandibles show insights on the dietary specializations of fossil taxa. *J. South Am. Earth Sci.* **2023**, *128*, 104445. [CrossRef]
42. Batallés, M.; Costoya, G.; Tambusso, P.S.; Varela, L.; Fariña, R.A. Megafauna 3D: Fossil digitalization for education, outreach and research. In Proceedings of the 1st Paleontological Virtual Congress, Virtual, 1–15 December 2018; p. 43.
43. Di Giacomo, M.; Batallés, M.; Varela, L.; Tambusso, P.S.; Clavijo, L.; Fariña, R.A. Keeping old giants at the service of a local community: The Arroyo del Vizcaíno collection (Sauce, Uruguay). *Geol. Curator* **2020**, *11*, 263–274. [CrossRef]
44. Fariña, R.; Di Giacomo, M.; Batallés, M.; Tambusso, P.S.; Varela, L. Conocimiento presente para la sociedad: La mirada de la paleontología en un caso de vínculo con la comunidad. *Tecnol. Y Soc.* **2020**, *9*, 69–93.
45. Fariña, R.A.; Tambusso, P.S.; Varela, L.; Czerwonogora, A.; Di Giacomo, M.; Musso, M.; Bracco, R.; Gascue, A. Arroyo del Vizcaíno, Uruguay: A fossil-rich 30-ka-old megafaunal locality with cut-marked bones. *Proc. R. Soc. B Biol. Sci.* **2014**, *281*, 20132211. [CrossRef]
46. Batallés, M.; Varela, L.; Tambusso, P.; Di Giacomo, M.; Fariña, R. *Megafauna en el Arroyo del Vizcaíno*; Udelar, FC: Montevideo, Uruguay, 2021.
47. Fariña, R.A.; Tambusso, P.S.; Varela, L.; Di Giacomo, M.; Musso, M.; Gascue, A.; Bracco, R. Among others, cut-marks are archaeological evidence: Reply to 'Archaeological evidences are still missing: A comment on Fariña et al. Arroyo del Vizcaíno Site, Uruguay' by Suárez et al. *Proc. R. Soc. B Biol. Sci.* **2014**, *281*, 20141637. [CrossRef]
48. Fariña, R.A.; Tambusso, P.S.; Varela, L.; Velazco, S.; Di Giacomo, M.; Gascue, A. Arroyo del Vizcaíno: Strengths and weaknesses of a very old archaeological/paleontological site in Uruguay, South America. In *New Discoveries in the American Paleolithic: The Pre-16,000 Archaeological Record, Conference Proceedings*; Jefferson, G., Holen, K.A., Holen, S.R., Eds.; Sunbelt Publications, Inc.: Chula Vista, CA, USA, 2021; pp. 21–28.
49. Fariña, R.A.; Tambusso, P.S.; Varela, L.; Gascue, A.; Stafford, T.W. Hard Facts in an Imperfect Site: The Evidence of Human Presence in the Arroyo del Vizcaíno. Reply to Holcomb et al. *PaleoAmerica* **2022**, *8*, 307–314. [CrossRef]
50. Domínguez-Rodrigo, M.; Baquedano, E. Human Agency in the Modification of *Lestodon* Bones at Arroyo del Vizcaíno? A Reply to Holcomb et al. *PaleoAmerica* **2022**, *8*, 300–306. [CrossRef]
51. Varela, L.; Lobato, C.; Tambusso, P.S. 3D model related to the publication: Presence of the ground sloth *Valgipes bucklandi* (Xenarthra, Folivora, Scelidotheriinae) in southern Uruguay during the Late Pleistocene: Ecological and biogeographical implications. *MorphoMuseuM* **2021**, *7*, 1–2. [CrossRef]
52. Varela, L. 3D model related to the publication: Occurrence of the ground sloth Nothrotheriops (Xenarthra, Folivora) in the Late Pleistocene of Uruguay: New information on its dietary and habitat preferences based on stable isotope analysis. *MorphoMuseuM* **2023**, *9*, 1–2. [CrossRef]
53. Varela, L.; Tambusso, P.S. 3D models related to the publication: 3D Finite Element Analysis and Geometric Morphometrics of Sloths (Xenarthra, Folivora) Mandibles Show Insights on the Dietary Specializations of Fossil Taxa. *MorphoMuseuM* **2023**, *9*, 1–3. [CrossRef]
54. Barbasiewicz, A.; Widerski, T.; Daliga, K. The analysis of the accuracy of spatial models using photogrammetric software: Agisoft Photoscan and Pix4D. In *E3S Web of Conferences*; EDP Sciences: Les Ulis Cedex A, France, 2018; Volume 26; p. 00012.
55. Mugnai, F.; Tucci, G. A comparative analysis of unmanned aircraft systems in low altitude photogrammetric surveys. *Remote Sens.* **2022**, *14*, 726. [CrossRef]
56. Cignoni, P.; Callieri, M.; Corsini, M.; Dellepiane, M.; Ganovelli, F.; Ranzuglia, G. Meshlab: An open-source mesh processing tool. In Proceedings of the Eurographics Italian Chapter Conference, Salerno, Italy, 2–4 July 2008; Volume 2008; pp. 129–136.

57. Fedorov, A.; Beichel, R.; Kalpathy-Cramer, J.; Finet, J.; Fillion-Robin, J.C.; Pujol, S.; Bauer, C.; Jennings, D.; Fennessy, F.; Kikinis, R.; et al. 3D Slicer as an image computing platform for the Quantitative Imaging Network. *Magn. Reson. Imaging* **2012**, *30*, 1323–1341. [CrossRef] [PubMed]
58. Potenziani, M.; Callieri, M.; Dellepiane, M.; Corsini, M.; Ponchio, F.; Scopigno, R. 3DHOP: 3D heritage online presenter. *Comput. Graph.* **2015**, *52*, 129–141. [CrossRef]
59. Ponchio, F.; Dellepiane, M. Fast decompression for web-based view-dependent 3D rendering. In Proceedings of the 20th International Conference on 3D Web Technology, Crete, Greece, 18–21 June 2015; pp. 199–207.
60. Tisue, S.; Wilensky, U. Netlogo: A simple environment for modeling complexity. In Proceedings of the International Conference on Complex Systems, Boston, MA, USA, 16–21 May 2004; Volume 21; pp. 16–21.
61. Musaeus, L.H.; Musaeus, P. Computational thinking in the Danish high school: Learning coding, modeling, and content knowledge with Netlogo. In Proceedings of the 50th ACM Technical Symposium on Computer Science Education, Baltimore, MD, USA, 21–24 February 2019; pp. 913–919.
62. Kuhn, J. Minecraft: Education edition. *Calico J.* **2018**, *35*, 214–223. [CrossRef]
63. Rivera Vargas, P.; Cobo, C. Plan Ceibal en Uruguay: Una política pública que conecta inclusión e innovación. In *Políticas Públicas Para la Equidad Social*; Rivera-Vargas, J., Muñoz-Saavedra, J., Morales Olivares, R., Butendieck Hijerra, S., Eds.; Colección Políticas Públicas: Santiago, Chile, 2018; pp. 9–26.