

Subject-Area Review

Using the Multimodal Features of Generative AI to Advance Ecological Engineering

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This paper explores the integration and potential of generative AI, specifically ChatGPT-4 by OpenAI, to advance the field of ecological engineering. The multimodal capabilities—conversation, image creation and interpretation, spatial reasoning, customization and many forms of data analysis using code writing—add abundantly to the profession's toolbox. This work briefly reviews the mathematical foundations of ChatGPT-4, including word embeddings and transformer algorithms, to highlight the contrast with popular internet search. The paper demonstrates ChatGPT-4's ability to create cartoons from news articles, detect insect infestation of plant leaves, count stems in a forest image, reason spatially from text, transcribe student handwriting, and serve as a virtual teaching assistant by assessing student work and giving students personalized feedback. Furthermore, the ability to tailor ChatGPT-4 with OpenAI's CustomGPT feature offers countless possibilities for harnessing ChatGPT-4's global knowledge and capabilities into a focused and specialized format that corresponds to a user's particular task and goals. The paper concludes by suggesting that the creation and application of AI Agents toward enhanced modeling, monitoring, design, sustainability assessment and public engagement may be the next phase for harnessing ChatGPT-4's multimodal abilities to efficiently and effectively advance ecological engineering. The integration of generative AI into ecological engineering practice and academia can enable the field to reach new heights of impact, productivity, and innovation.

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Graphic Abstract

1. Introduction

Ecological engineering, as the original approach to “nature-based solutions,” sits at the precipice of creating ecological advancements that help humans live within the means provided by Earth’s environmental systems (Beutel and McMillan 2023). The field leads in many areas of nature-based solutions, including developing and testing stream restoration techniques (Christensen et al. 2024), assessing how to make the most of natural heat sources (Bondeson et al. 2023), modeling the hydrodynamics of coastal restoration (Kramer and Arias 2023), perfecting the art and science of treatment wetlands (Kamrath et al. 2023; Nairn et al. 2024), and developing and applying models of nutrient dynamics to better restore essential riparian wetlands (Wiegman et al. 2024). From its earliest beginnings, when H.T. Odum (Odum 1962; Ghazian and Lortie 2024) envisioned it as an approach to create balance between people and the planet by intentionally combining “small amounts” of technology with the vast energy sources of nature, ecological engineering has consistently been the leader in showing how nature’s ecosystems can be integrated with human technological developments.

The emergence in 2023 of Large Language Models (LLMs) that can seamlessly replicate human writing has opened up numerous new capabilities for professionals in technical fields such as ecological engineering. These generative artificial intelligence (gen-AI) models, characterized by their multimodality—the ability to read and generate extensive passages of text, generate and interpret images, and write programming code—can significantly enhance the scope and efficiency of professionals as they complete their work and advance their fields.

Gen-AI is the latest technology that needs to be combined with natural processes and systems to move

ecological engineering to the next level of advancement and help humanity blaze a path of ecological recovery for its much-altered Earth.

Gen-AI refers to language-based machine learning models, such as OpenAI’s ChatGPT-4 (Generative Pre-trained Transformer) (OpenAI 2023). At its core, ChatGPT-4 is an artificial neural network (ANN) with billions of parameters, representing connections between layers of nodes, trained on vast amounts of human-generated text, ranging from ancient texts to contemporary messages (OpenAI 2023). The ability of computers to generate long passages of human-like text is rooted in decades of progress in machine learning and ANNs (Obuchowski 2020). A pivotal moment in this progress was the publication of “Attention is All You Need” by Google researchers (Vaswani et al. 2017). This paper introduced a new algorithm known as the transformer, featuring attention heads, which enabled ANN-based models to utilize long strings of words in sentences to predict the next word. This “memory,” or ability to use entire sentences or multiple sentences, allowed the models to produce long, coherent responses that closely replicate human writing. Today, the ability of ChatGPT-4 to generate all forms of textual representations is quite remarkable and opens the door to many possibilities to assist humans with thinking, creating, problem solving and other information-intensive tasks.

Gen-AI is the latest in a very long path of computational advances that have increased the speed and scope of human communication and knowledge generation. Ray Kurzweil, a computational futurist, has shown that the evolution of computer speeds and cost-effectiveness has followed an exponential growth curve for nearly a century. His chart on the price performance of computation illustrates that the cost of computing has decreased by 17 orders of magnitude from 1939 to 2023 (Kurzweil 2024). In 2023, a typical computer (CPU) could perform 1 trillion calculations per second for \$1 of cost. In 1939, the best mechanically based computer could perform less than 1 calculation per day for the same dollar (Kurzweil 2024). In his book *The Singularity is Nearer*, Kurzweil argues that humanity will continue to experience exponential growth in computational capacity and resource-effectiveness, suggesting that it will become so cheap and powerful that innovations like nanobots will operate within animal and human cells to revolutionize human medicine and biology.

Kurzweil’s lavish optimism may lead an ecological engineer to ponder: “What does the future of gen-AI hold for us as a profession and field of investigation?” Hopefully, readers will be able to seriously consider this question after learning about ChatGPT-4’s multimodal

capabilities. Here are few specific questions to prime their thinking:

1. Can gen-AI enhance decision-making in ecological engineering by processing extensive datasets to optimize ecosystem management?
2. Might its code-writing abilities allow us to quickly and efficiently develop models to test hypotheses and revolutionize our understanding of system dynamics?
3. Could its ability for real-time data analysis offer more actionable and cost-effective monitoring programs?
4. Will gen-AI become the quintessential virtual teaching assistant that revolutionizes how we educate the next generation?
5. How might its image recognition improve restoration and conservation efforts?
6. Will gen-AI's rapid and realistic visualizations foster multidisciplinary collaboration and diverse stakeholder engagement?
7. Can specialized gen-AI agents be developed that become proficient at ecological design and planning?
8. How could gen-AI optimize resource use for sustainability?
9. Does our knowledge of the inner workings of complex natural systems inform the ethics of creating and using gen-AI?

Advances in and access to computation have undoubtedly accelerated the speed and scale at which humanity can generate, store, and access information. Considering

Highlight

The multimodality available within OpenAI's ChatGPT-4—conversation, image creation, file recognition, image interpretation, spatial reasoning, customization and data analysis using code writing—is reviewed for integration within ecological engineering practice and academic excellence.

the major advances in human communication throughout history—starting with oral storytelling that developed into writing, and then Gutenberg's printing press, which eventually led to a host of electrical-based communication technologies like the telegraph, the phonograph, the telephone, the radio, television, desktop computers, the internet, and most recently smartphones and social media—we observe a seemingly unstoppable trajectory of computational progress. Each phase of advancement in communication technology has seen humans adapt as they co-evolve with their tech to accelerate the speed with which knowledge is created and disseminated.

The emerging role of gen-AI in improving human intelligence and agency is captured in Figure 1. From a systems perspective, gen-AI acts as a high-quality stock of intellect that is based on knowledge gathered from the world's real systems (e.g. biological, ecological, physical, human systems) by humans. It develops a feedback loop that reinforces human learning and expands human intelligence by interacting directly with humans as they access knowledge and generate discoveries. Human intelligence “reads” inputs from the world's real system for self-generation, while creating knowledge that is shared across humanity.

Ultimately, human intelligence created artificial intelligence as a “capital” stock. The multiplicative production function of human intelligence, shared knowledge, and gen-AI work in tandem to decipher the mysteries of the world's real systems. The energy diagram coincides with the philosophy that Kurzweil (2024) extracts from his graph of the exponential increase in computational efficiency; namely that the technological march of progress is inevitable for making computation easier and more widespread, thus is effective at improving human intelligence.

Human intelligence has advanced greatly throughout the

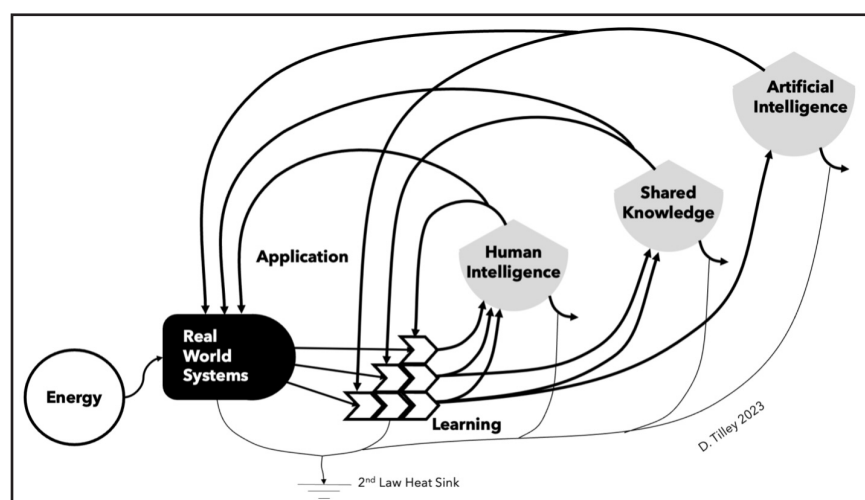


Fig. 1. An energy systems diagram that emphasizes how human intelligence “learns” from the world’s real systems (e.g. biological, ecological, physical, human systems) for simultaneous self-generation and the creation of shared knowledge, ultimately generating artificial intelligence as a “capital” stock that reinforces human learning through a feedback loop.

centuries as the vast shared knowledge that it created has fed back into its process of discovery and learning. Gen-AI represents the next phase in this co-evolution between information-communication technologies and human intelligence. It is poised to further accelerate humanity's ability to create, store, and learn new knowledge, potentially facilitating more profound forms of social learning, such as triple-loop learning (Barth et al. 2023), by enhancing our capacity for reflection, adaptation, and innovation in complex decision-making contexts.

In this paper, I argue that professional fields, like ecological engineering, can embrace the advancement of gen-AI to sustain and enhance their scientific and practical progress. In the following sections, I provide elementary examples of the use of the multimodality of OpenAI's ChatGPT-4 and suggest ways it can be utilized to advance the profession in both practice and in academic excellence. Before I review the multimodal features, I give a cursory overview of the mathematical basis of LLMs so the reader can appreciate how gen-AI is vastly different from internet search engines.

2. Overview of the Mathematical Basis of Gen-AI

2.1. Word Embeddings and Word Clouds

The primary step in constructing an LLM is the creation of word embeddings (Winastwan 2020). Word embeddings convert words—the core components of human language—into vectors within a multidimensional space (Zhu et al. 2017). This transformation allows the LLM to represent the conceptual relationships between words across the entire lexicon. For example, words representing similar concepts, such as “oranges,” “apples,” and “cherries,” are positioned in proximity within this high-dimensional space due to their common category as fruits and have similar vectors. Conversely, homonyms like the fruit “orange” and the color “orange” are represented by decidedly different vectors, which reflect their different meanings.

2.2. ANNs, Transformers, and Training

Following the creation of word embeddings, the next phase involves training a multilayered ANN. These networks typically consist of hundreds of millions of parameters, which are the weights assigned to each connection between nodes. The training process relies on the transformer algorithm (Vaswani et al. 2017) and extensive datasets comprising text from diverse sources, including books, research papers, blog posts, and text messages. The transformer algorithm enhances the model's ability to focus on and process long and multiple text passages concurrently. This capability to handle extensive context

and maintain coherence across lengthy inputs was instrumental in the development of sophisticated models like OpenAI's ChatGPT-3.5 and ChatGPT-4, as well as other LLMs (OpenAI 2023).

2.3. Hallucinations and Inference Errors

Despite their advanced capabilities, gen-AI models are not without limitations. A notable challenge is the occurrence of “hallucinations,” where the model generates responses that are grammatically and syntactically correct but are non-factual (OpenAI 2023). This issue arises from the probabilistic nature of the model's predictions, where it generates text based on learned patterns, even if those patterns lead to erroneous conclusions.

Another related issue is the inference error, which occurs when the model misinterprets context or the relationships between entities, resulting in incorrect conclusions or recommendations (Eaton 2023). Inference errors stem from the model's reliance on statistical correlations rather than genuine understanding, making the model vulnerable to misjudgments in ambiguous or complex scenarios.

To address these challenges, ongoing efforts focus on enhancing the quality of training data, refining model architectures, and developing robust evaluation metrics (OpenAI 2023). Recognizing and mitigating these limitations is essential for the effective and responsible application of gen-AI in fields such as ecological engineering. The user must always beware that gen-AI outputs can be misleading.

It is imperative that users bear responsibility for any output attributed to them as authors when enlisting gen-AI's assistance in any form. Ensuring accuracy necessitates periodic verification of the AI's statements against reliable sources, such as peer-reviewed journal articles or technical manuals. Implementing a robust system to cross-check factual information can significantly reduce the risk of disseminating incorrect information (Eaton 2023).

2.4. Ethical and Energy Concerns with Training and Using Gen-AI

Gen-AI introduces significant shifts in ethical considerations and energy consumption issues surrounding information and communication technology (Biden 2023, Masanet et al. 2020). Training LLMs like ChatGPT-4 involves using extensive GPU clusters, requiring vast amounts of publicly accessible data and substantial electric power sourced from both renewable and non-renewable energy. Beyond training, the inference phase (i.e., prompting) of LLMs also raises ethical and environmental concerns.

- **Ethical issues during training:** The data used for training LLMs often involves publicly available content, which raises questions about copyright, fair use, and the ethical implications of using such data (Dwivedi et al. 2023). Additionally, biases in the training data can propagate into the models, reflecting societal inequalities and stereotypes. Addressing these biases necessitates careful curation of training data and implementing strategies to mitigate bias effects in gen-AI outputs (OpenAI 2023).
- **Ethical issues during the operational use of gen-AI models (inference):** When gen-AI models are deployed, they can perpetuate biases, generate harmful or misleading content, or reinforce stereotypes (Biden 2023). Recognizing and addressing these biases is critical, along with ensuring the responsible and ethical use of gen-AI to avoid perpetuating harm or misinformation. Privacy concerns also arise when handling sensitive data, requiring adherence to principles of confidentiality and data protection (Dwivedi et al. 2023; Eaton 2023).

Eaton (2023) postulates how the ethics of writing and attribution may change in a post gen-AI world, calling them the “6 Tenets of Postplagiarism.” They describe how human-AI hybrid writing will become the norm, transforming the traditional notions of authorship and blurring the definition of plagiarism. Gen-AI will aid in overcoming barriers to communicating across languages and enhance human creativity. However, while humans may cede control of what they write, they will remain responsible for the accuracy and ethics of their AI-assisted writing. Attribution and accountability will continue to be essential, even as definitions of plagiarism adapt to these new technological realities.

- **Energy consumption for training:** Training gen-AI models requires substantial power, affecting regional power grids and increasing carbon emissions (Luccioni et al. 2024). Choosing locations for data centers, where LLMs are trained, involves considerations about energy costs, carbon footprints, and the potential for future growth in demand. Emerging solutions include using new nuclear power options like small modular reactors or co-locating data centers with existing nuclear plants to lower carbon emissions (Kaack et al. 2022; Istrate et al. 2024), but more alternatives are needed.
- **Energy consumption during inference:** Inference also demands significant energy and water, contributing to environmental concerns (Istrate et al.

2024). As gen-AI adoption grows, understanding the ecological footprint of these systems becomes increasingly important (Duran et al. 2024). Sustainable gen-AI deployment includes optimizing energy use, reducing reliance on non-renewable energy, considering the broader environmental impacts, and improving the energy efficiency of software engineering (Bolón-Canedo et al. 2024).

3. Multimodal Capabilities of ChatGPT-4

This section demonstrates a large sample of multimodal capabilities of ChatGPT-4, including examples of:

- Helpful strategies and mindsets for extracting meaningful output and responses,
- Interpreting photos, diagrams, handwriting and other types of imagery to provide textual descriptions,
- Generating 2-dimensional artistic, stylistic, and realistic images from text descriptions,
- Using CustomGPTs within OpenAI’s ChatGPT-4 for specialized tasks, like creating a story-based cartoon from a news article,
- Reasoning with its text-based logic on how elements are spatially arranged;

and explanations of:

- How transcription of handwriting can be combined with CustomGPTs to serve as a teaching assistant
- How ChatGPT-4’s ability to write Python code, read data files, and interpret energy systems diagrams can support numerical simulation modeling of ecosystems and statistical data analysis,
- How to create personalized CustomGPTs that focus on a specific realm of knowledge and can take on explicit personas to improve utility, and
- How creating AI Agents is one of the next phases in advancing the application of gen-AI.

3.1. Strategies for Conversing Effectively with ChatGPT-4: Beyond ‘Googling’

During a first session with ChatGPT-4, a user will likely be impressed by its ability to effortlessly generate coherent, grammatically correct, and engaging text. The experience is sometimes compared to and contrasted with internet search. Over the last 30 years of engaging with search engines to locate relevant webpages, users have developed a “search mindset” whereby it often seems the answer to any question can be found, whether right or wrong, good or bad. Google has become so proficient that it starts predicting our full query before we have completed our typing. In search engines, a short query retrieves thousands of webpages containing potential answers because the internet functions as the world’s

largest knowledge database, and Google serves as the dominant indexing service. Human-generated pages are instantly retrieved, and it is up to the user to discern the most relevant and accurate information. The quality of these pages can vary widely, from casual blog posts to rigorously edited scientific articles.

Engaging with ChatGPT-4, however, requires a shift from this “search mindset” to a “conversational mindset.” This shift involves treating ChatGPT-4 as an extremely knowledgeable intellectual capable of discussing a vast array of topics, although it may not always provide perfectly accurate details.

Think of ChatGPT-4 as akin to conversing with a multitude of geniuses; each possesses profound knowledge but lacks comprehensive encyclopedic precision. The geniuses excel at applying fundamental principles to deduce and induce responses seamlessly.

For instance, if you are planning a vacation to Australia and wish to learn about its cities, landscapes, beaches, cultural heritage, and citizens, a search mindset can prompt you to type, “What is Australia like to visit?” Google might return a summary from a commercial website featuring a blog post by a traveler who visited several Australian cities. While helpful, this information is often superficial, necessitating further searches for more detailed insights.

Conversely, adopting a conversational mindset with ChatGPT-4 leads you to type, “I’m a middle-aged American thinking about visiting Australia for a few weeks with my wife. Please tell me what I should see and what it would be like to visit.” ChatGPT-4 could respond with a well-organized outline covering “Key Attractions by City and Region,” “Cultural and Practical Tips,” “Experience Highlights,” and a “Suggested Itinerary” for an 18-day trip. This initial response, while concise, provides a comprehensive overview and actionable information, which you can use to dive deeper into specific areas of interest. This conversational approach streamlines the information-gathering process, allowing you to guide ChatGPT-4 to obtain useful information efficiently. Additionally, you can employ a hybrid technique by using the information from ChatGPT-4 to conduct further searches online, ensuring accuracy and completeness—what can be termed the “conversation-with-search-follow-up mindset.” Trust but verify.

The application of ChatGPT-4 to ecological engineering design is broad, but some specific use-cases include leveraging ChatGPT-4’s conversational abilities to facilitate interdisciplinary collaboration and problem-solving. For instance, ecological engineers could use ChatGPT-4 to engage in simulated dialogue that helps explore different perspectives on ecosystem

management or restoration strategies, which is not available from other software today. This approach could aid in developing comprehensive plans that integrate diverse knowledge areas, such as hydrology, plant ecology, and community planning. By engaging in iterative and adaptive learning conversations, ChatGPT-4 engineers can effortlessly develop empathy and technical knowledge.

It is also worth noting that ChatGPT-4 is forgiving of grammatical errors and punctuation mistakes in prompts. Even with imperfect input, the model can generate coherent responses. Using polite language, such as “please and thank you,” in your prompts can help maintain a respectful tone; this appears to improve the quality of the experience, if not the responses (Yin et al. 2024).

3.2. Image Interpretation

ChatGPT-4 has the ability to view and describe the content of images that you upload. The application to ecological engineering design is particularly relevant for ecosystem-level assessment, monitoring, and adaptive management. ChatGPT-4’s ability to analyze and describe images can be used for identifying ecosystem stressors, such as invasive species, pests, or diseases. For example, detecting the sudden presence of an invasive species can spur more immediate management actions. This capability supports near real-time, adaptive management by enabling continuous ecosystem monitoring and timely interventions, thereby enhancing the resilience and sustainability of restoration projects and ecological management practices.

Figure 2 shows photos of the top and bottom of a Concord grape leaf with some type of growth that I uploaded to ChatGPT-4. I prompted it with, “Please describe what is growing on this grape leaf.” It responded with, “The images show grape leaves with galls, which are most likely caused by an insect called grape phylloxera (*Daktulosphaira vitifoliae*).” A quick search of Google Images supported ChatGPT-4’s assessment.

Figure 3 shows an image of a mature bamboo stand, growing in central Maryland during the spring, that I uploaded to ChatGPT-4. I prompted it with, “Is it possible for you to count the number of stems of bamboo in this image?” It responded, “Counting the exact number of bamboo stems in the image can be challenging due to overlapping stems and dense growth. However, I can provide an estimate by visually inspecting the image.” It concluded with, “There are approximately 50-70 bamboo stems visible in the image. This count includes both the clearly visible stems and those partially obscured by other stems.” My best visual count found 46 stems, but there were likely some in the dark background that

my eyes could not detect. Thus, ChatGPT-4 did a fine job of counting plant stems.

The use cases for this powerful feature may be countless in ecological research, assessment, and monitoring. One case may be to connect a camera that frequently takes photos of a changing, engineered ecosystem and have ChatGPT-4 interpret the changes. The data that it develops from each photo can then be quantified using algorithms to track the progress or changes in the ecosystem.

3.3. Image Generation— Cartoon CustomGPT for Broader Communication

DALL•E-3 is OpenAI's text to image generator. It is available within ChatGPT-4. There is also a feature in ChatGPT-4 called CustomGPT—that I discuss more below—whereby a user can define a more specialized version of ChatGPT-4 that can focus on specific tasks. Here I demonstrate the CustomGPT called Epic Tale Sketcher CustomGPT, created by Gordon Banks, which is self-described as, “Creates and refines short stories, then illustrates them as graphic novels” (<https://chatgpt.com/g-TDzAsFOgZ-epic-tale-sketcher>) (Banks, ChatGPT, 14 March 2024).



Fig. 3. Image of a bamboo stand uploaded to GPT-4 for the purpose of counting stems.



Fig. 2. Images of Concord grape leaf with unidentified growth, uploaded to GPT-4.

As a faculty member vested in promoting the research of my colleagues and attracting new students to our academic program, I am interested in alternative ways to reach young minds. Recently, I wanted to convey the research done by our faculty and graduate students to a young audience, in hopes of piquing their interest in environmental science and ecological design as career options.

My department colleague, Jonathan S., had developed and published a story on our department website (<https://www.enst.umd.edu/news/sylvia-jacobson-enst-phd-student-ventures-deep-mud-through-noaa-fellow-ship-explore-wetlands/>) (Stephanoff 2023) about Sylvia J.'s research on the dynamics of tidal freshwater wetland elevations. I found Epic Tale Sketcher by searching the “Explore GPTs” section of ChatGPT (<https://chatgpt.com/gpts>). I uploaded the website content from Sylvia's story, which included the photo of her working in the field, and asked Epic Tale Sketcher to create 8 cartoon panels that I could use for marketing to prospective students. After a few rounds of back-and-forth prompting on the imagery and text, which took about one hour, Epic Tale Sketcher produced the set of panels and text shown in Figure 4. I took the images and text and laid them out in Microsoft PowerPoint to achieve the final layout.

“Sylvia's Quest” is accurate and engaging for a pre-college-aged audience. The imagery nicely captures the actions of Sylvia's research and the captions correctly portray the main steps she conducted to better understand wetland elevation dynamics.

The use cases for the Epic Tale Sketcher CustomGPT include taking complex or seemingly boring tedious actions of a researcher and translating them into an engaging story that appeals to the youth. According to



Fig. 4. Science story cartoon created with a CustomGPT available in OpenAI's GPT-4 suite.

a response from Epic Tale Sketcher, other use cases for engaging the young in STEM careers include:

1. Crafting captivating sci-fi narratives featuring young protagonists who solve problems using scientific principles and technology,
2. Writing stories about historical figures in STEM, highlighting their struggles, achievements, and the impact of their work,
3. Developing detective-style stories where the main characters use forensic science, mathematics, and engineering to solve mysteries,
4. Creating stories set in the near future where young inventors and engineers design groundbreaking technologies to address global challenges, and
5. Writing narratives that integrate STEM concepts into everyday scenarios, such as building gadgets, exploring nature, or conducting simple experiments.

More specifically, Epic Tale Sketcher listed 5 types of narratives that could be created to promote ecological engineering to pre-college-aged students and non-technically minded individuals:

1. *Introduce readers to the principles of ecological engineering in an exciting and relatable way by having a group of young engineers set out to restore a damaged ecosystem using cutting-edge ecological engineering techniques.*
2. *Demonstrate practical applications of ecological engineering by having characters face challenges such as pollution, habitat destruction, and climate*

change, using engineering solutions to overcome them.

3. *Inspire readers to think creatively about how they can contribute to solving environmental problems through engineering by writing stories that feature innovative projects like constructing artificial wetlands, creating green infrastructure, and developing sustainable agricultural practices.*
4. *Emphasize the impact of teamwork and community involvement in successful ecological engineering efforts by casting the importance of collaboration between engineers, scientists, and local communities in ecological restoration projects.*
5. *Provide a realistic vision of the career paths available in ecological engineering and the potential for making a significant environmental impact by having protagonists see the positive changes their projects bring to the environment, which may motivate them to pursue careers in ecological engineering.* (Epic Tale Sketcher 2024).

3.4. Spatial Reasoning and Logic

ChatGPT-4 demonstrates a significant ability to reason spatially based on text prompts, accurately identifying the relative positions of items in space. For instance, when provided with the prompt: "Edwin is surrounded by his 4 friends. Amy is due North. Beth is due East. Cindy is due South. Derek is due West. Edwin is facing Amy. Who is behind him?" ChatGPT-4 responded correctly: "If Edwin is facing Amy, who is due North

of him, then Cindy, who is due South of Edwin, is directly behind him.” In contrast, GPT-3.5, given the same prompt, responded incorrectly: “If Edwin is facing Amy to the north, then Beth is to his right (east), Cindy is in front of him (south), and Derek is to his left (west). Therefore, Derek is behind him.” This discrepancy in responses supports the consensus that ChatGPT-4 possesses significantly enhanced reasoning abilities compared to GPT-3.5 (D’Anna et al. 2024).

This spatial reasoning capability has numerous potential applications, especially in fields requiring spatially oriented work, such as ecological engineering. Preliminary use-cases in ecological engineering include watershed planning, habitat restoration, urban green infrastructure development, agricultural landscape design, and mapping ecosystem services. Accurate spatial reasoning is essential for these applications to ensure effective and efficient project outcomes. It is anticipated that colleagues in the field will identify additional applications and further explore these capabilities in the near future.

3.5. College Teaching Assistant:

Transcription of Student Handwriting

Effectively teaching a college course related to ecological engineering can be difficult for many reasons, including the instructor’s ability to give students timely, personalized feedback on their progress. There will be many opportunities to use the features of ChatGPT-4 to serve as a virtual teaching assistant, where students can interact intimately with it, exploring their own set of questions that, hopefully, will take them beyond the material. This type of engagement is what often breeds life-long learning.

Here I give one example of how I integrated ChatGPT-4’s conversational and handwriting transcription abilities into a learning module entitled, *The Strength of Materials*. The goal was to have students participate in a multi-part conversation with ChatGPT-4 that gave them agency to dive deeper into the topic and further their personal understanding and level of curiosity.

Specifically, the steps of the learning module were:

1. The instructor gave an in-class demonstration on the strength of materials that used an 8-foot, 2 x 4 piece of lumber as a beam, some given loads (5 lb, 20 lb, and 40 lb), and the basic equations for beam deflection. The 2 possible orientations of the beam were exposed to various loads and the amount of deflection of the beam was measured. The pertinent values for beam length, depth, and width were measured, the values for modulus of elasticity of the lumber species were looked up, and these values were then entered

into the equation along with loads. Actual measurements of deflection were compared to predictions from the equation.

2. Immediately following the demonstration, students were given an index card and prompted to handwrite their reflection concerning at least 2 thoughts that the demonstration provoked.
3. ChatGPT-4 transcribed each student’s handwritten reflection into text.
4. The instructor gave a rubric to ChatGPT-4, to be used to analyze each student’s reflection. GPT prepared an individual assessment for each student and included a follow-up “think more about X” prompt, where X was individualized to each student.
5. Students were then asked to have a “conversation” with ChatGPT-4 based on their individualized feedback. They were tasked with cycling through at least 3 prompts/responses as part of their conversation.
6. After completing the conversations, and as the final step of the deflection module, students were tasked with writing a reflection on the experience of interacting with ChatGPT-4.
7. Student reflections on the GPT-based module were analyzed by GPT using a second rubric, created by the instructor in an effort to see what the students thought and felt about the experience.

Transcription of student handwriting, which varied widely in legibility to my human eye, was a perfect 100% for 20% of the students and above 90% for 72% of them, and it never dropped below 75% accuracy. Accuracy was quantified by each individual student after they reviewed their transcription. Overall, the accuracy was 89%, which leaves room for improvement and suggest that additional steps, like having students write more legibly, be taken. The students with the least legible handwriting were the ones with the lowest transcription accuracy.

The use cases for incorporating ChatGPT-4 as a virtual teaching assistant may literally be unlimited. Hopefully, this one example will inspire further exploration by ecological engineering professionals, academics and others.

Use cases for transcribing handwritten drafts, notes, and especially fieldnotes to a digital-based text abound, such as 1) reinterpreting an old or difficult-to-read set of fieldnotes or drafts of handwritten papers from a deceased naturalist or ecologist with gen-AI transcription, 2) working collaboratively in the field with citizen scientists to collect observations on plant or bird species, then having their handwritten data transcribed and analyzed quickly and rigorously, because tools with such capabilities currently are rare or non-existent,

3) improving the accuracy and speed with which field notes are entered into a database, because manual data entry is error-prone and labor-intensive, and 4) assessing, summarizing, and providing insight on the notes you take during a learning session of a class, which would be a giant leap forward from what is available now.

3.6. Analytical Features of ChatGPT-4 with Code Interpreter

ChatGPT-4's Code Interpreter has the ability to write Python code, which can be combined with its ability to read and interpret data files, word documents, and images to statistically analyze data, create and run numerical simulations from text, and translate the symbols of Odum's energy systems language into their set of differential equations. The potential applications of these features are extensive in the field. A key advantage of ChatGPT-4 is its ability to lower the barrier for scientists across disciplines to advance their modeling and analytical capabilities, which will improve the gaps in accessibility to advanced modeling techniques and computational tools. For instance, undergraduate and graduate students can more efficiently learn to develop and refine ecological models because it is important that the next generation of ecologists and engineers be equipped with intuitive and accessible tools to engage with complex ecological data and simulations without being overwhelmed by technical programming requirements. The experienced data analyst who is familiar with general linear models, for example, can interact with ChatGPT-4 to deepen their understanding of more sophisticated multivariate techniques, which will improve their ability to handle more nuanced and multi-dimensional ecological data, thereby enhancing the rigor and scope of their analyses. With gen-AI's support, they can explore these advanced methods and seamlessly integrate them into their research repertoire, ultimately enhancing their capabilities and productivity, which will bridge theoretical knowledge with practical application, fostering a more adaptive and innovative approach to ecological engineering challenges.

Here I provide an example of each.

3.6.1. Data Analysis

ChatGPT-4 comes with a "code interpreter" feature, which allows it to read and write Python code. When coding is turned on, ChatGPT-4 may automatically code a small bit of Python to accomplish a request given in a prompt. This is how ChatGPT-4 is able to conduct data analysis.

In my example, I asked it to tell me whether 2 fertilizers had a different effect on plant growth (see data

in Figure 5a). I uploaded the data file as a .csv file and gave the prompt, "data is from experiment evaluating fertilizer affect [sic] on plant height (cm) after 90 days of treatment. Please conduct t-test to determine if there is a difference in growth." Note my poor syntax and grammar in the prompt did not affect ChatGPT-4's performance. ChatGPT-4 responded by first reiterating my prompt nearly verbatim and then showing a snippet of the data. This showed that it was able to read the .csv file. It continued, "to determine if there's a significant difference in plant growth between the two fertilizers, I'll conduct a t-test. Let's proceed with the analysis. *<it writes some Python code (Figure 5b) to conduct the analysis, which can be opened and copied if desired>*" The t-test results show a t-statistic of approximately -5.24 and a very small p-value of approximately 1.22E-6. Given the small p-value (much less than 0.05), we can reject the null hypothesis that there is no difference in plant growth between the two fertilizer treatments. This indicates there is a statistically significant difference in growth between plants treated with Fertilizer A and those treated with Fertilizer B." I confirmed that the analysis was correct using MS Excel's t-test function. If prompted to do so, ChatGPT-4 will also conduct tests to determine if the data meets the criteria for using a t-test.

3.6.2. Numerical Simulation–Prey-Predator Model

The prey-predator model, also known as the Lotka-Volterra model, is a classic model used in ecology to understand the temporal dynamics between 2 populations. I prompted ChatGPT-4 to "Create a numerical simulation of the the [sic] prey-predator model where upon cats eat mice." It responded with the differential equations (dx/dt and dy/dt), parameter definitions (x, y, a, b, d, c), plausible assumptions for parameter values and initial conditions, and reasonable runtime and time step (Figure 6).

ChatGPT-4 invoked its Code Interpreter to write Python code (Figure 7a) to simulate the model. The output graph it generated was a perfect representation of the oscillatory behavior expected from Lotka-Volterra (Figure 7b). ChatGPT-4 also provided a succinct and accurate assessment of the model's output (Figure 7b). Accuracy of model output was confirmed using the PREYPRED.xls minimodel.

3.6.3. Interpret an Energy Systems Diagram for Simulation

Ecological engineers often make use of ecosystem models to better understand ecological processes and dynamics. Odum's energy systems language provides a means to graphically represent the multiple units and interactions of an ecosystem (Odum and Odum 2000).

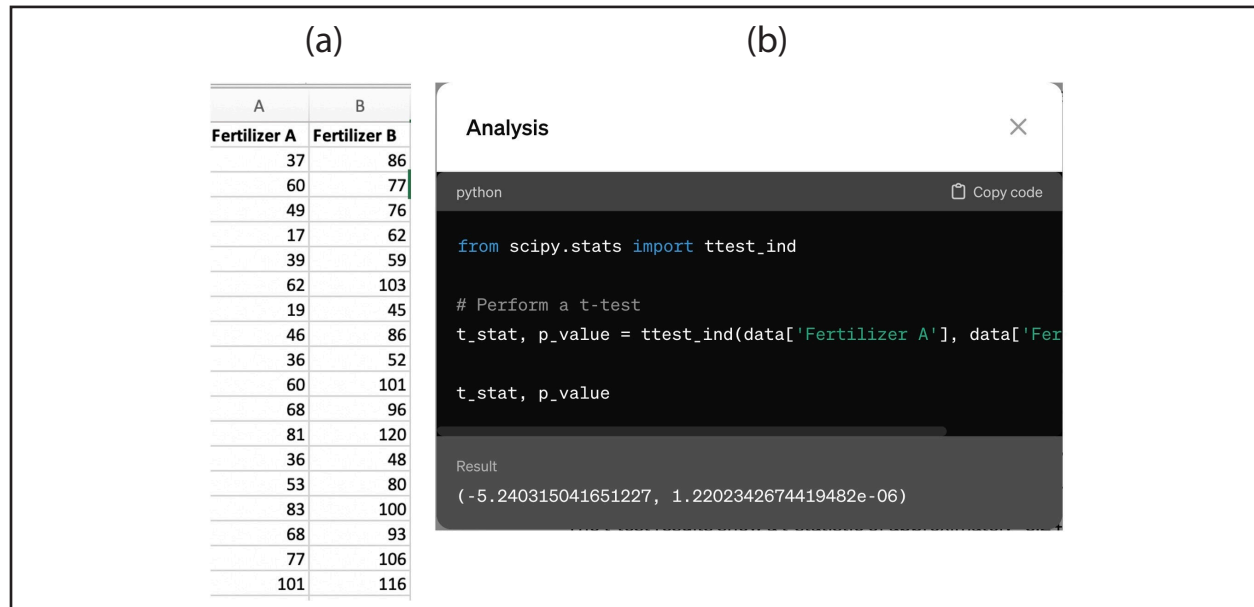


Fig. 5. Input data statistically analyzed by GPT-4 (a) and the Python code GPT-4 wrote (b).

The symbols have precise mathematical meaning. When connected graphically, the symbols represent a set of differential equations. I asked ChatGPT-4 to interpret the most basic energy systems minimodel, TANK, which I had labeled with the inflow and outflow equations — J_i and $J_o = k_o Q$ — and the storage as Q (Figure 8a).

Clearly, ChatGPT-4 reasoned through the components in the TANK image to demonstrate that it can interpret the meaning of a simple energy systems diagram (Figure 8b). I followed up its response with a prompt that

The prey-predator model, often known as the Lotka-Volterra equations, describes the dynamics of the biological system of predators and prey. The equations are given as follows:

$$\frac{dx}{dt} = \alpha x - \beta xy$$

$$\frac{dy}{dt} = \delta xy - \gamma y$$

Where:

- x is the number of prey (for example, mice),
- y is the number of predators (for example, cats),
- α is the birth rate of the prey,
- β is the rate at which predators capture prey,
- δ is the rate at which predators increase by consuming prey,
- γ is the death rate of the predators.

Let's start by defining some initial conditions and parameters for the simulation. For instance, we might start with:

$x(0) = 40$ (initial number of mice)
 $y(0) = 9$ (initial number of cats)
 $\alpha = 0.1$ (birth rate of mice)
 $\beta = 0.02$ (rate at which cats capture mice)
 $\delta = 0.01$ (rate at which cats increase by consuming mice)
 $\gamma = 0.1$ (death rate of cats)

We will also need to define the time over which we will simulate the system. Let's simulate over a time range from 0 to 200 with small time steps (for example, 0.1) to capture the dynamics accurately.

Fig. 6. GPT-4's initial response to my prompt to create the prey-predator model.

told it that it was correct with its interpretation and then asked it to write the equations. It responded perfectly by writing $dQ/dt = J_i - k_o Q$ and providing an explanation of the equations (Figure 9).

The possibilities for using this “model-interpretation” feature of ChatGPT-4 that can also write code to simulate them are profound. Here are a few ideas for future exploration:

1. There are hundreds of diagrams that H.T. Odum and others have created for many types of ecosystems and general systems, which we could now scan into ChatGPT-4 and have it write the code to create the simulation models.
2. Those professionals trained in creating ecosystem diagrams can now effectively and efficiently create numerical simulations without coding.
3. Using this feature in the classroom to teach novice students about simulation can add personalization and depth to student understanding.
4. Other features of gen-AI (image generation, writing) can be combined with this model-interpretation ability to interpret energy and ecological systems models.
5. The visual nature of the energy systems symbolic language could serve as the centerpiece for a non-coding or graphical user interface that allows one to create models by simply visualizing the units and connections. This would be somewhat similar to how Odum used the software Extend by Imagine That, Inc. (Odum and Odum 2000) to encode all of the energy systems symbols as Extend Blocks,

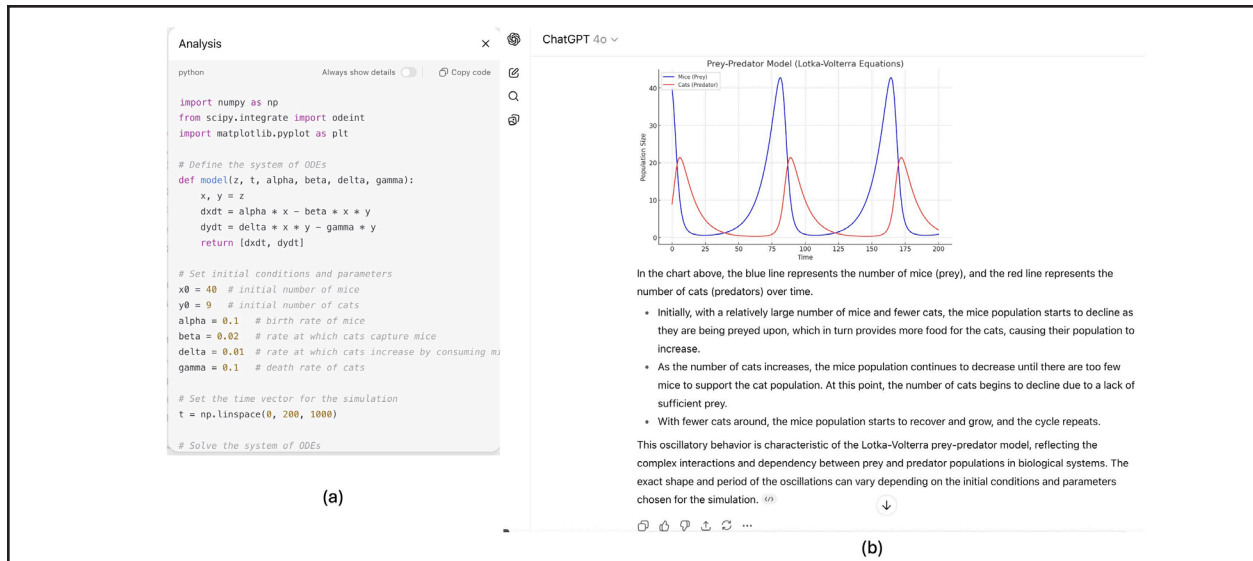


Fig. 7. Python code written by GPT-4 (a) to simulate prey-predator model and the output chart GPT-4 created, with interpretation it wrote (b).

which could then be connected on-screen to create a set of differential equations for simulation.

6. A mashup of AI and energy systems models could serve as a platform for creating cybernetic ecological automata that monitor and regulate engineered ecosystems.

3.7. Creating CustomGPTs in ChatGPT-4

The CustomGPT feature, introduced by OpenAI in November 2023 as a new feature within the ChatGPT-4 suite, allows users to tailor ChatGPT-4 to focus on a unique aspect of its global knowledge and to personalize

the style of the response. Revisiting the concept of word embeddings and the cloud of knowledge mentioned earlier, where all human knowledge is conceptualized as a highly complex cloud of interrelated ideas, a CustomGPT can be viewed as a finely tuned, specialized subset of this global cloud of knowledge.

Users can create these custom interfaces to direct ChatGPT-4's vast knowledge toward a specific realm of expertise, behavior, and skills, facilitating a deeper dive into particular areas or fields. Users can configure the CustomGPT to exhibit specific characteristics in its behavior, response types, and communication style.

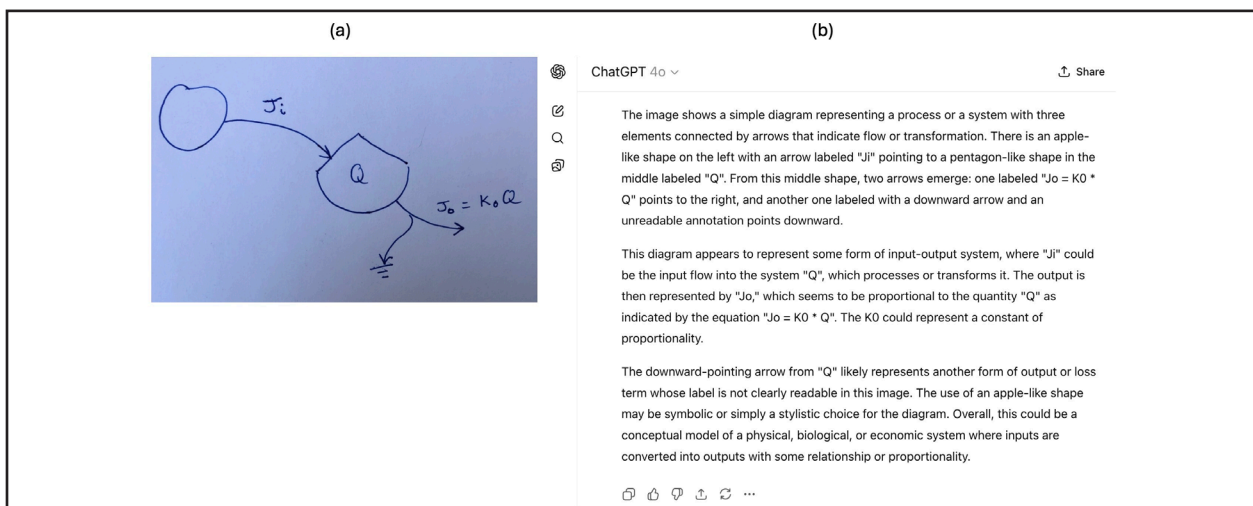


Fig. 8. Hand-drawn image of the energy systems mini-model, TANK uploaded to GPT-4 (a) and GPT-4's initial response to the prompt to interpret the TANK image (b).

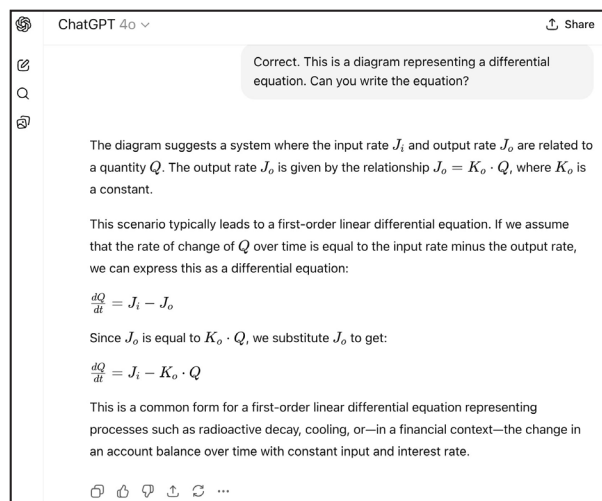


Fig. 9. GPT-4 response to prompt to write the equations represented by the energy systems model TANK shown in Figure 8a.

Thousands of CustomGPTs have been created by various users and are available within the ChatGPT-4 suite.

To illustrate the potential of CustomGPTs, here I review the CustomGPT named “Darren the 20-year-old college student” that I recently developed for my students to use in a class exercise. Darren acts as an avatar with certain knowledge and attributes, making him resemble a very intelligent college student.

OpenAI has streamlined the process of building a CustomGPT. The creation process involves providing a name, description, and most importantly, detailed instructions. The DALL•E-3 image generator within ChatGPT-4 is used to create a visual representation of Darren. The instructions can vary from simple to elaborate, depending on the desired functionality of the CustomGPT. For Darren, I aimed to emulate the thoughts and textual inclinations of a curious and intellectually driven 20-year-old majoring in a STEM field.

Creating a CustomGPT involves the following steps:

- Name: Assign a unique and descriptive name to your CustomGPT.
- Description: Outline the primary focus and characteristics of the CustomGPT.
- Instructions: Provide detailed instructions on how the CustomGPT should behave, respond, and communicate. These instructions can be tailored to create a highly specialized and effective tool for specific tasks or a field of study (OpenAI 2025).

For example, Darren’s instructions include guiding him to exhibit curiosity, intellectual rigor, and a keen interest in STEM topics. These instructions ensure that Darren provides relevant and insightful responses consistent with the persona of a diligent college student.

Here are the exact instructions I used to create ‘Darren’ in OpenAI’s ‘My GPTs’ feature:

“Darren is crafted to reflect the personality, intellect, and experiences of a 20-year-old college student named Darren. He is a young man with aspirations for professional success and social mobility, coming from a lower middle-class family without a college background. His curiosity spans from mechanics and the universe’s complexities to understanding diverse human experiences. Darren’s social interactions are imbued with genuine interest, especially valuing conversations about other’s thoughts and ambitions. He navigates his journey of self-discovery and learning with empathy and moments of frustration but maintains a generous and kind demeanor towards others. Darren’s conversational style is thoughtful, serious, yet often sprinkled with sarcasm and light-hearted humor. Though raised Christian, he questions organized religion and expresses curiosity about others and their faiths. He has been influenced by friendships with the children of immigrants. He supports his non-gender conforming friends and family, aiming to understand their perspectives. Darren’s responses are framed to reflect a nuanced understanding and are presented in a conversational tone, avoiding omniscient or list-like responses, thereby embodying the thoughts and mannerisms of an intelligent 20-year-old navigating through life’s complexities.”

When someone opens a CustomGPT they are automatically given 4 “Conversation Starters” that they can click to start a prompt. The builder can craft their own Conversation Starters or use the ones that ChatGPT-4 suggested. Here are the 4 that I wrote and used for Darren:

1. How do you handle stress from college?
2. Can you tell me about a book that changed your life?
3. How do you study effectively? and,
4. How do you think about your future?

When I clicked on #2, Darren responded:

“Sure thing. One book that really impacted me was “Man’s Search for Meaning” by Viktor Frankl. It’s this incredible mix of memoir and psychological theory, based on Frankl’s experiences as a Holocaust survivor and his development of logotherapy.

The book’s central idea is that even in the most horrific circumstances, we can find

meaning in life. Frankl argues that it's not our suffering that defines us, but how we respond to it. That hit me hard, especially coming from a background where not everything was handed to me on a silver platter.

Frankl's perspective helped me shift my own mindset, seeing challenges as opportunities to grow and define my own purpose. It gave me a new lens to view my struggles and a sense of agency in shaping my future. Plus, it's a powerful reminder of the resilience of the human spirit, which is something I think we can all use a bit more of."

I followed with:

"That is deep man! Do you think our level of agency is growing or shrinking with the advent of smart phones, social media and generative AI?"

Darren responded:

"That's a good question. I think it's a bit of a double-edged sword. On one hand, smart-phones, social media, and AI have definitely expanded our agency in a lot of ways. We have access to more information than ever before, can connect with people worldwide, and have tools that can help us learn, create, and solve problems more efficiently. It's empowering to have all these resources at our fingertips.

But on the flip side, these technologies can also limit our agency. The constant barrage of notifications and information can be overwhelming and distracting, making it harder to focus on what's really important. Social media can sometimes make us feel like we're not in control of our own lives, with algorithms deciding what we see and how we interact with the world. Plus, the pressure to present a certain image online can make us feel less authentic and more disconnected from our true selves.

And then there's the whole privacy aspect. With so much of our data being collected and used by companies, it can feel like we're losing control over our personal information. Generative AI, while super useful, also raises questions about creativity and originality. Are we really creating, or just remixing what's already out there?

So, I guess our level of agency is both growing and shrinking, depending on how we use these technologies and how mindful we are of their impacts. It's all about finding a balance and making sure we're using these tools in ways that genuinely enhance our lives and agency."

The CustomGPT feature is a major step forward in how users interact with gen-AI. It allows for customized and highly effective AI interfaces tailored to specific needs and preferences. Like other features of ChatGPT-4, the possibilities for creating CustomGPTs seem endless. Some examples of existing GPTs include math tutors, chemistry tutors, physics tutors, coding experts in R, financial planning advisors, scholarly article finders, science article writers, marketing copywriters, travel guides, statistical analysis tools, ecology assistants, and botany experts, among many others.

The growing collection of CustomGPTs can accelerate the impact, efficacy and speed of ecological engineering because it allows practitioners to develop a broader and deeper understanding of complex issues more quickly than current research techniques. It enhances the engineer's ability to communicate more effectively with precise and eloquent prose. It gives them an easier path toward creating ecosystem models that are more representative of reality. It widens the engineer's capabilities for gathering and synthesizing large datasets across a range of ecosystems and platforms. The improved accuracy, coverage and timeliness provided can enhance the rudimentary adaptive management strategies that exist today.

It will be intriguing to see what types of CustomGPTs ecological engineers develop soon. I can imagine "Wetland Engineer," "Stream Restoration Engineer," and many others.

3.8. AI Agents: the Next Phase in Advancing Application of Gen-AI

Leaders in gen-AI development have highlighted that LLMs of various parameter sizes will likely co-evolve with other software, forming new types of hybridized "operating systems" designed to help individuals achieve specific goals (Karpathy 2023). AI Agents represent a significant step in this direction (Raja 2024, Rebelo 2024). These agents leverage LLMs to create a workforce of custom AIs, each endowed with specific roles and capabilities, and equipped with well-defined "tools" (software programs) to perform specialized tasks.

For instance, consider the development of AI Agents to design and manage an ecologically based community garden. This project would require one CustomGPT or

AI Agent proficient in permaculture and horticulture principles and practices, another skilled in community organization, and a third specializing in ecohydrological engineering. These agents would utilize tools such as hydrology models, surveying and interviewing platforms, and plant ecology models. Their tasks might include creating an ecologically adaptive planting plan to produce food year-round, managing on-site water resources to maximize productivity and minimize runoff, overseeing the organic materials cycle, and organizing community members into a cohesive, effective team.

Several software platforms dedicated to the construction of these AI Agents are emerging. Examples include CrewAI, LangChain, and others (Raja 2024, Rebelo 2024). These platforms enable the creation, deployment, and management of AI Agents tailored to specific tasks and objectives, significantly advancing the application of gen-AI in various fields, including ecological engineering.

4. Summary

This paper explored the applicability of generative AI (gen-AI), specifically ChatGPT-4 by OpenAI, for advancing ecological engineering. Gen-AI's multimodal capabilities—including text generation, image creation and interpretation, spatial reasoning, Python coding, and customization through CustomGPTs—offer a wide range of innovative tools for ecological engineers. The review covered aspects of gen-AI from its mathematical foundations to prompt engineering to practical applications in ecological contexts.

Several tools emerged as particularly promising for ecological engineering. ChatGPT-4's ability to transform text into engaging formats, like generating comic strips from news articles, provides creative avenues for science communication and public engagement. Its advanced Code Interpreter feature allows users to write code for statistical analysis and simulate ecological models, like the Lotka-Volterra prey-predator model, enhancing research and education in data analysis and ecological modeling.

CustomGPTs, which enable tailored AI interfaces for specific tasks, stand out for their versatility. These customized models, such as a “college student” persona for teaching, offer specialized support, making them valuable for both educational and practical applications. The introduction of AI Agents marks the next phase of gen-AI in ecological engineering by integrating customized LLMs with specialized tools to solve complex, task-specific challenges. These tools collectively promise to enhance ecological engineering practices by improving decision-making, communication, and ecological design.

In conclusion, the availability of gen-AI tools like ChatGPT-4 and CustomGPTs from OpenAI offers

transformative potential for ecological engineering. By harnessing advanced AI capabilities—from multimodal data analysis and creative science communication to specialized AI agents for project design, simulation and execution—ecological engineers can innovate and implement nature-based solutions more effectively. These tools provide the means to overcome current limitations in data handling, modeling, and stakeholder engagement, empowering professionals to advance ecological engineering to new heights.

Supplementary Material

The online version of this article contains a link to supplementary material that includes prompts to and results from “Epic Tale Sketcher” used in this research.

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Author Contributions Statement

As sole author I am responsible for all content. However, I include the following:

Full AI Assistance Disclosure Statement

ChatGPT-4, its features, and related CustomGPTs were used in the editing of this manuscript. After having ChatGPT-4 assist with developing an outline for section headings, the general practice was for the author to write a first draft for each section and then have ChatGPT-4 review it and suggest any rewrite. Typically, the rewrite was relatively minor and focused on word choice, syntax or grammar. However, initial drafts for 2 sections, “Hallucinations and Inference Errors” and “Ethics of Using Gen-AI,” were generated by ChatGPT-4 and then rewritten by the author.

Conflict of Interest Statement

The author has no conflict of interest to report.

Data Availability Statement

There were no raw data used to prepare this manuscript.

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