Stanford University
Human-Centered
Artificial Intelligence

January 2023
Industry Brief
An initiative of HAI Industry Programs & Partnerships

Sustainability and AI

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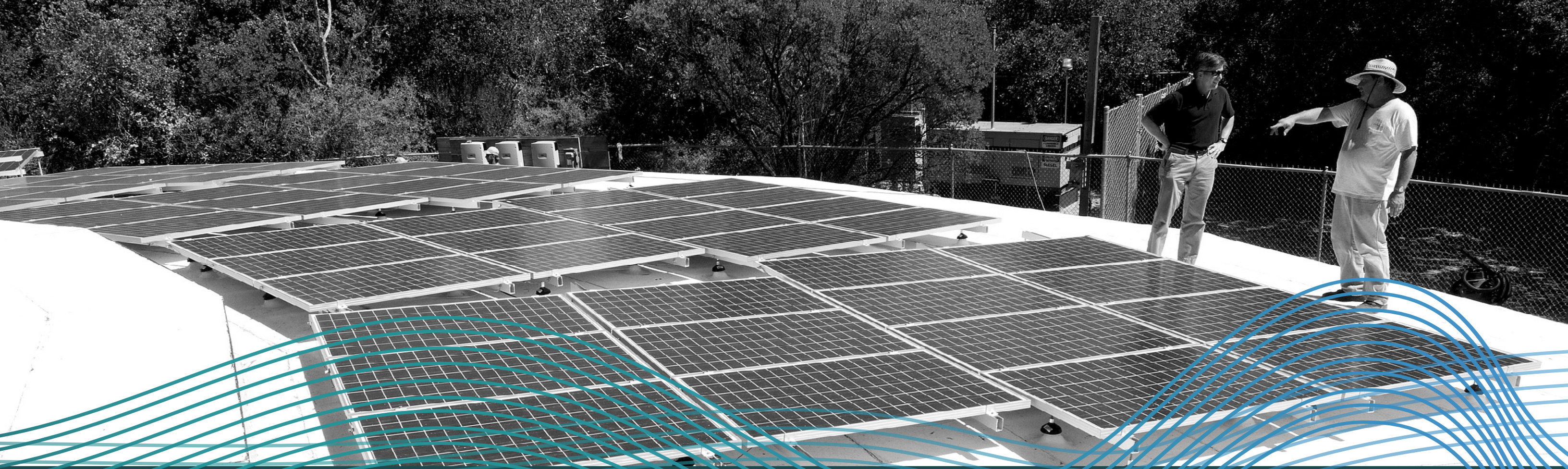

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Introduction

Our ability to prosper for generations to come depends on the condition of our biosphere, as human and planetary health are intrinsically interconnected. A sustainable world is one where we improve the quality of our lives while protecting Earth's ecosystems. However, we are still far from achieving sustainability and the challenges we face are significant. The world's population is projected to grow from 8 billion in 2022 to 9.8 billion by 2050[1], increasing demand for energy, urban services, and animal protein. Access to resources changes drastically based on where in the world we are, with close to 193 million people acutely food insecure and in need of urgent assistance across 53 countries and territories[2], while urban populations are projected to make up 68% of the world's population by 2050[3]. Extreme weather events are occurring with unprecedented frequency and reshaping the world's socioeconomic outlook.

We do, however, have the tools to build a sustainable world. Recent developments in Artificial Intelligence (AI) are helping us see issues that were hard to identify before. As machine vision enables us to see our world, we are able to detect problems, track them, and create targeted interventions. The knowledge AI unlocks enables action, helping us measure and achieve environmental, social, and governance (ESG) goals. At the Stanford Institute for Human-Centered Artificial Intelligence (HAI), we are focused on leveraging AI methods and solutions to improve the human condition, augment human capabilities, and embed intelligence in our operations. In this brief, we examine innovations by Stanford researchers that use AI to shift our world from one that depletes resources to one that preserves them for the future. Since pursuing sustainability is a transdisciplinary challenge, we view the role AI plays across disciplines, from engineering to behavioral psychology.

James Landay
Anand Rajaraman and Venky Harinarayan Professor, School of Engineering, Professor of Computer Science, Stanford University; Vice-Director and Faculty Director of Research, Stanford HAI

HAI's mission is to advance AI research, education, policy and practice to improve the human condition. To learn more about HAI, visit hai.stanford.edu

1 Future Population Growth, Our World in Data
2 Global Report on Food Crises, 2022, WFP
3 Urbanization, Our World in Data

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Pamela Matson, Richard and Rhoda Goldman Professor of Environmental Studies and Senior Fellow at the Woods Institute for the Environment, Emerita

Scalable Sustainability Solutions

Sustainability challenges are highly complex. We need solutions that can scale across borders. To achieve this, systems approaches and collaboration across disciplines and sectors are essential. In pursuing sustainability, we need to ask who participates and what policies, norms and rules support or impede just and equitable well-being. AI technologies are helping us understand our complex interdependent systems, accessing knowledge that was previously invisible to the human eye. The promise of AI to help us scale towards a sustainable future is becoming exponentially clearer.

Satellite Monitoring of Development

Stefano Ermon
Associate Professor, Department of Computer Science, Stanford University

AI-powered machine learning (ML) tools can help extract and assess important sustainability information and metrics from satellite imagery—such as agricultural productivity, urban population density, and rural economic activity, making them an intriguing and valuable addition to the sustainable development toolkit. Yet many questions remain. In particular, researchers need to better understand how well these models can map satellite image inputs to sustainable development outcomes and what limits the models' performance. Our paper in *Science*, "Using Satellite Imagery to Understand and Promote Sustainable Development," outlines how researchers have used ML models to estimate sustainable development outcomes, assess methods for model training, examine the challenges hindering models' improvement, and consider models' future applications. We conclude by identifying current limitations to these approaches and ways to respond. As the number of non-military satellites in orbit continues to rapidly grow, we continue to tailor and train our methods to the unprecedented volumes of imagery in order to help measure and creatively use existing and new sustainable development outcomes.

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Sustainability Activities on the Stanford Campus

- AI for Climate Change Bootcamp
- Center for Ocean Solutions
- Center for Sustainability Data Science
- Center for Sustainable Development and Global Competitiveness
- Doerr School of Sustainability
- Environmental Change and Human Outcomes Lab
- MineralX Initiative
- Precourt Institute for Energy
- Stanford Center for Earth Resources Forecasting
- Stanford National Accelerator Laboratory
- Stanford Urban Informatics Lab
- StorageX Initiative
- Sustainability and Artificial Intelligence Lab
- The Natural Capital Project
- The Regulation, Evaluation, and Governance Lab (RegLab)
- TomKat Center for Sustainable Energy
- Woods Institute for the Environment
- Z-Energy

1 Sustainability and AI
Decarbonizing Energy Systems

★ WHAT'S NEW?

Our world is in need of rapid decarbonization across all industries, and first and foremost, in our energy systems. Stanford faculty are pioneering AI research in a range of fields across this sector:

Tracking Emissions

Emissions from the consumption of traditional energy sources need to be monitored, managed, and substantially reduced.

- Electricity: A real-time map **tracking the United States' electricity emissions** has been introduced by Adjunct Professor Jacques de Chalendar using a physics-informed data reconciliation framework. This insight can inform policymakers, regulators, and large consumers where to intervene to meet emissions goals. Interventions in this space are essential as the world shifts to electrification. This work also shines a light on environmental justice issues as high-emission-generating electricity does not benefit the communities most burdened from the air pollution it produces.
- Natural Gas & Methane: Associate Professor Adam Brandt and professor Rob Jackson use infrared imagery and automated monitoring systems to **track methane leaks from natural gas** which fuels our electricity, enabling targeted interventions that can reduce such leaks by 80%. There is also work being done to **track methane leaks from all possible sources** through METER-ML; a multi-sensor earth observation dataset containing georeferenced images in the U.S. labeled for the presence or absence of six methane source facilities.
- Rig infrastructure: To further attribute energy emissions to sources on the ground, deep learning algorithms that leverage high-resolution aerial imagery have been applied to **automatically detect oil and gas infrastructure worldwide.**

"To reach our net zero goals, we must create thorough, complex plans. This is challenging due to the inherent uncertainty and sequential nature of sustainability problems. For example, finding minerals critical to our transition to clean energy involves collecting data through measurement campaigns that are expensive and time-consuming. In our research, we use intelligent agents to reduce uncertainty in mineral exploration by optimizing the sequence of measurements. The results show a significant improvement in predictions and an increase in the speed of discovery of critical minerals."

-Jef Caers, Professor of Earth and Planetary Science and Professor (by courtesy) of Geophysics, Stanford University

1 Sustainability and AI
Decarbonizing Energy Systems

Continued

Renewable Energy

To accelerate the adoption of wind and solar energy worldwide, Stanford researchers have developed models called DeepWind and DeepSolar. These models use satellite imagery to **detect the location of wind turbines and solar panels**, enabling grid operators to integrate renewable energy sources into the grid. DeepSolar uses high-accuracy machine learning models to **predict solar adoption rates** based on environmental and socioeconomic factors correlated to current deployment. To plan for fluctuation in available solar energy, Stanford has developed probabilistic models to **forecast solar irradiance**, thus optimizing solar energy utilization in the grid.

Material Design & Energy Storage

Designing materials that can store and dispatch renewable energy where and when it is needed is key to creating carbon-neutral energy cycles. The Z-energy lab is using machine learning-assisted, data-driven approaches to **understand material systems for a range of energy applications**, including electrolysis for the production of hydrogen and hydrogen peroxide. The Chueh lab by Associate Professor William Chueh is researching how to **optimize technologies such as batteries, fuel cells, electrolyzers, and novel thermodynamic cycles**. Using new high-resolution microscopy techniques, Chueh and his team analyzed atomic-scale images through AI to understand why batteries wear out, with the ultimate aim of **creating longer-lasting batteries**. Increased demand in batteries and other clean energy infrastructure is boosting demand for critical minerals. Professor Jef Caers is pioneering research using intelligent agents to **extract Earth's resources more sustainably** with a lower environmental footprint.

"We can't manage carbon if we can't measure it. Decarbonization of electricity generation and simultaneous electrification of energy end use, including for heating, cooling and transportation, will have big impacts on electricity systems. Measuring the carbon content embodied in electricity is increasingly important and urgent to set goals and monitor progress. We have created algorithms and software to track energy and associated emissions and yield actionable data and insights by computing emissions embodied in production, trade and consumption in the US electricity sector."

-Jacques de Chalendar
Adjunct Professor, Energy Resources Engineering department, Stanford University

1 Sustainability and AI
Decarbonizing Energy Systems

Continued

WHY DOES THIS MATTER NOW?

Energy use is the single biggest source of greenhouse gas emissions, contributing to 76% of the world's emissions[1]. We need to meet the challenge of providing power to our communities without polluting and warming the Earth. There is an energy revolution unfolding as we transition from coal, oil, and natural gas use to sustainable energy sources such as solar and wind.

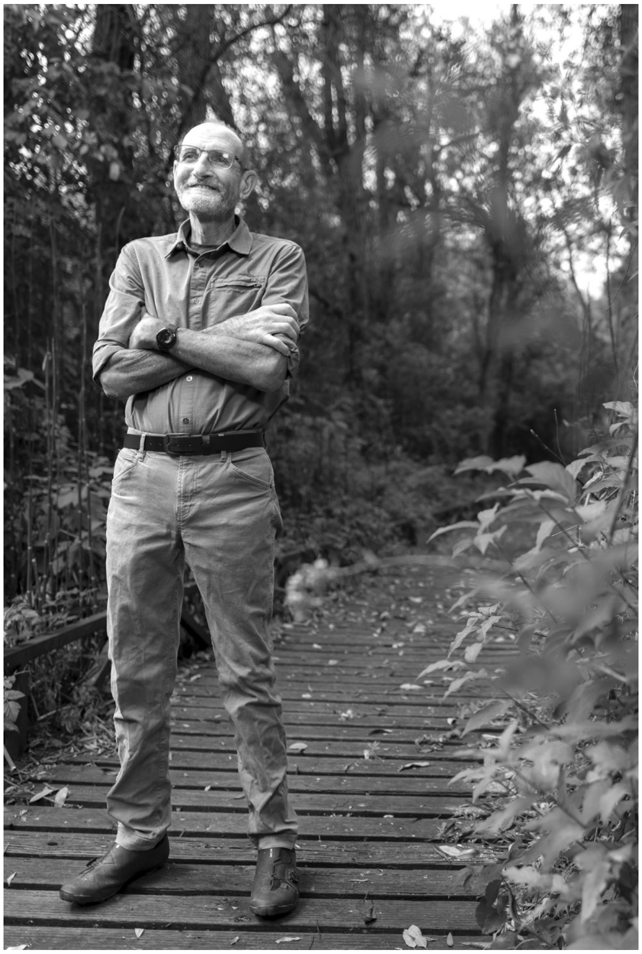
However, fossil fuels still supply approximately 80% of the world's energy[2]. As we undergo this transition, it's necessary to recognize that different parts of the world have very different energy landscapes. 13% of the world's population has no access to electricity and 40% has no access to clean fuels for cooking[3]. It is necessary to create targeted solutions that address equity and human health. For the portion of the world with access to electricity, power outages due to weather events have increased dramatically in the last 10 years. In the United States, there has been a 78% increase in outages, which are estimated to cost between 10 and 100 billion dollars annually[4]. This is why it is essential to increase the resilience of our grid.

Targeting solutions to address methane leaks specifically can have an oversized impact on slowing warming. That's because the 1% of greenhouse gas (GHG) emissions that come from methane can heat the Earth more than the 99% from CO2[5]. As methane only lasts around 10 years in the atmosphere, intervening today to eliminate methane leaks from natural gas production would be one of the fastest ways to slow down climate change.

The path toward clean energy requires the extraction of critical minerals, such as lithium, cobalt, nickel, and copper. The production of essential infrastructure, such as solar panels, electric vehicles, and battery storage, requires more minerals than traditional fossil fuel technologies[6]. This huge spike in demand will change the landscape of global supply chains.

Read more:

1 Climate Data for Action, Climate Watch Data
2 Fossil Fuels, Environmental and Energy Study Institute (EESI)
3 Access to Energy, Our World in Data
4 Surging Weather-Related Power Outages and Surging Power Outages and Climate Change, Climate Central
5 Cutting Methane Emissions Could Slow Global Warming Rate by 30%, Environmental Defense Fund (EDF)
6 The Role of Critical Minerals in Clean Energy Transitions, International Energy Agency (IEA)

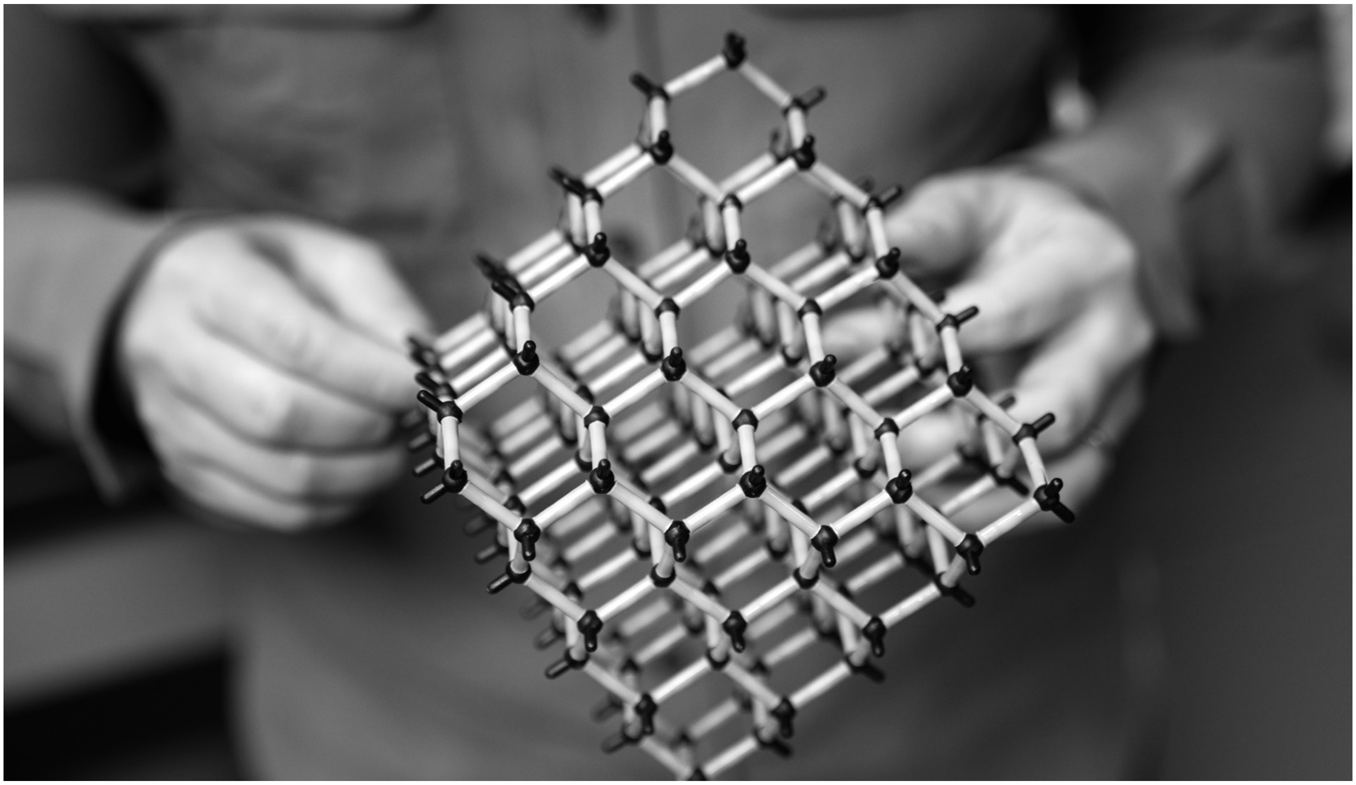


1 Sustainability and AI
Decarbonizing Energy Systems

Continued

EYE ON CAMPUS

- DeepSolar: A Machine Learning Framework to Efficiently Construct a Solar Deployment Database in the United States
- Short-Term Solar Irradiance Forecasting Using Calibrated Probabilistic Models
- DeepWind: Weakly Supervised Localization of Wind Turbines in Satellite Imagery
- METER-ML: A Multi-Sensor Earth Observation Benchmark for Automated Methane Source Mapping
- Machine Vision for Natural Gas Methane Emissions Detection Using an Infrared Camera
- Intelligent Prospector v1.0: Geoscientific Model Development and Prediction by Sequential Data Acquisition Planning With Application to Mineral Exploration
- Correlative Image Learning of Chemo-Mechanics in Phase-Transforming Solids
- OGNet: Towards a Global Oil and Gas Infrastructure Database Using Deep Learning on Remotely Sensed Imagery
- Tracking Emissions in the US Electricity System
- A Physics-Informed Data Reconciliation Framework for Real-Time Electricity and Emissions Tracking
- Chueh Lab
- Z-Energy Lab



2 Sustainability and AI
Accelerating Sustainable Agriculture

★ WHAT'S NEW?

Industrial agriculture has dominated food production in a way that is not sustainable, relying on large monoculture farms that use chemical pesticides and fertilizers that damage our soil, water, air, and climate. An alternative approach is one that enables farms of all sizes to contribute to their local economies yet uses resources more efficiently, creates access to healthy food for all, and prioritizes communities and soil health over short-term corporate interests.

To achieve some of these goals, researchers at Stanford are developing AI algorithms that use satellite imagery to:

- **Identify crop types, segment fields and understand and predict crop yield variation.** This information has traditionally been measured through low quality and low frequency surveys.
- **Measure soil moisture, plant moisture and plant health,** thus optimizing water use. These measures have traditionally only been available through hardware sensors.
- **Measure and correlate crop greenness and nitrogen oxides** (NOx). The latter can directly damage crop cells and indirectly affect growth by promoting ozone (O3) and aerosol formation. Professor David Lobell and his team studied five major agricultural regions and estimated that reducing NOx levels to the current fifth percentile would raise yields by roughly 25% for certain regions and times of year.

These breakthroughs provide highly more cost-effective and scalable ways to manage crops and ensure efficiency in resource use like water.

"Nitrogen oxides are invisible to humans, but new satellites have been able to map them with incredibly high precision. Since we can also measure crop production from space, this opened up the chance to rapidly improve our knowledge of how these gases affect agriculture in different regions. In our recent Globally Ubiquitous Negative Effects of Nitrogen Dioxide on Crop Growth study, we reveal for the first time how nitrogen oxides—gases found in car exhaust and industrial emissions—negatively affect crop productivity."

-David Lobell, Earth System Science, and Gloria and Richard Kushel Director of the Center on Food Security and the Environment, Stanford University

2 Sustainability and AI
Accelerating Sustainable Agriculture

Continued

To maintain a healthy supply of groundwater for drinking and agricultural practices, strategies to treat water need to be developed. Professor Jef Caers uses intelligent agents to **plan groundwater remediation strategies**, optimizing the trade-off between information gathering and the performance of possible future scenarios. The results yield much better groundwater remediation strategies than hand crafted heuristics and optimization methods, hence enabling more sustainable management of this vital resource.

Livestock feeding operations contribute heavily to emissions and pollution. Stanford is finding ways to tackle this issue by developing models that **identify Concentrated Animal Feeding Operations** (CAFOs) and hold them accountable for regulation violations - more on this in the 3rd section of this brief. These methods are expected to **reduce regulatory violations** and thereby lessen the impact of these feeding operations on the health of the planet.

WHY DOES THIS MATTER NOW?

The food sector contributes over 20% of total GHG emissions, 60% of which comes from meat, while the agri-food chain accounts for approximately 30% of the world's total energy demand[1]. Geopolitical and climatic events are impacting the food system's resilience. It is estimated that 795 million people still live without an adequate food supply[2]. By 2050, there will be 2 billion more people to feed[3]. Establishing sustainable food security for the future and ending hunger are primary goals in the United Nations' 2030 Agenda for Sustainable Development[4]. The severity and number of people in crisis in 2022 has increased[3] due to persistent conflict, economic shocks, and weather extremes, which are predicted to worsen as the effects of climate change become more prevalent.

"Sustainable investment decisions take environmental, social, and governance (ESG) considerations into account. As of today, investment funds that use ESG have more than $50 trillion in capital. However, current ESG metrics lack transparency and are mostly about the internal costs as well as impacts of company operations. To achieve societies' goal of ecological sustainability and social justice, which is the dream of stakeholder capitalism, new metrics of ESG must be developed that involve consumers in order to help them to collaborate with ESG goals, as well as external ESG metrics that measure the impact of companies on the communities in which they operate."
-Alex Pentland, Visiting Scholar, Stanford Digital Economy Lab, Stanford University, and Toshiba Professor of Media, Arts and Sciences, Massachusetts Institute of Technology

2 Sustainability and AI
Accelerating Sustainable Agriculture

Continued

Read more:

1 "Energy-Smart" Food for People and Climate, FAO

2 The State of Food Insecurity in the World 2015, FAO

3 The Water, Food, Energy and Climate Nexus: Challenges and an agenda for action

4 Transforming Our World: The 2030 Agenda for Sustainable Development

Global Report on Food Crises, World Food Programme

Standards and Investments in Sustainable Agriculture, 2022, International Institute for Sustainable Development

Sustainable Agriculture and Food Systems: Comparing Contrasting and Contested Versions, 2022, Chatham House

The Rising Risk of a Global Food Crisis, 2022, McKinsey

Sustainable Agriculture Market Intelligence Report, 2022, GreenCape

EYE ON CAMPUS

- Globally Ubiquitous Negative Effects of Nitrogen Dioxide on Crop Growth
- Satellite-Based Assessment of Yield Variation and Its Determinants in Smallholder African Systems
- Deep Gaussian Process for Crop Yield Prediction Based on Remote Sensing Data
- Semantic Segmentation of Crop Type in Africa: A Novel Dataset and Analysis of Deep Learning Methods
- Satellite Imagery, AI and Efficiency in Agricultural Water Use
- A Sequential Decision-Making Framework With Uncertainty Quantification for Groundwater Management
- Higher Levels of No-Till Agriculture Associated With Lower PM2.5 in the Corn Belt
- Satellites Reveal a Small Positive Yield Effect from Conservation Tillage Across the US Corn Belt

3 Sustainability and AI
Informing Environmental Policy

★ WHAT'S NEW?

Environmental monitoring is essential for enforcing regulations and creates a new avenue for planning policy as it becomes evident where and what types of interventions are needed. Advances in technology, such as deep learning neural networks, have made it possible to train models to monitor our world using high resolution satellite imagery and computer vision. For example, **tracking methane emissions** from all possible sources through METER-ML, as outlined in the 1st section of this brief, can drive policy, as the efficacy of targeted interventions can now be monitored and therefore enforced. Tracking emissions is also a pathway for policy making in the field of AI itself. Peter Henderson has built a model that **tracks emissions of AI** and suggests carbon reduction methods.

Partnering with agencies that can create and enforce environmental law is key to creating lasting change. Researchers Dan Ho and Jenny Suckle are collaborating with the EPA to develop machine learning methods for environmental monitoring. Professor Ho's work **detects Concentrated Animal Feeding Operations (CAFOs) and monitors *Clean Water Act*[1] violations**, such as dumping highly polluting manure into water sources, in near real-time. Another example is the **identification of brick kilns**, a highly polluting industry in Bangladesh. These are low-cost methods for governments and agencies that have traditionally lacked the ability to locate and monitor distributed polluters to enforce regulation.

Deep learning is also being used to **understand the drivers of deforestation** in Indonesia to inform policy and conservation efforts, as well as **understand the causes of extreme weather events**. We can thus visualize the potential impacts of different management interventions to **better plan for wildfire events and flooding mitigation**.

"Many of our environmental institutions were built in the 1970s. The mainstay of environmental monitoring has been self-reporting by facilities or physical inspections that might occur once every few years. The sharp growth in satellite and aerial imagery, coupled with powerful advances in computer vision, holds the promise to leapfrog over conventional forms of environmental monitoring."

–Daniel E. Ho, Benjamin Scott and Luna M. Scott Professor of Law at Stanford Law School, Professor of Political Science, Senior Fellow at the Stanford Institute for Economic Policy Research, Associate Director of the Stanford HAI, and Director of RegLab

3 Sustainability and AI
Informing Environmental Policy

Continued

WHY DOES THIS MATTER NOW?

To protect the Earth's resources for generations to come, policy and regulations are necessary to correct market failures that do not account for the preservation and flourishing of essential ecosystem services. Methane emissions are heating the planet faster than CO2[2]. As alluded to in the Sustainable Agriculture section of this brief, CAFOs violating environmental protection policies has a substantial impact on pollution, as they produce between 70% and 99% of the United States' pigs, cows and chickens[3]. The number of acres across the country burned by wildfires has quadrupled in the last four decades[4].

It is necessary to develop policies that incentivize communities and institutions to fix these failures. It is also important to be able to enforce such policies cost effectively, which has historically been difficult both within countries and across international borders. Machine vision can help us achieve both these goals. Our work is already helping agencies like the EPA, which has relied on self-reporting in the past, create accountability and protect the natural resources we depend on.

Read more:

1 Clean Water Act

2 Methane: A crucial opportunity in the climate fight, EDF

3 What is a CAFO?, Food Industry

4 U.S. Fires Quadrupled in Size, Tripled in Frequency in 20 Years, Eos

"Enforcing environmental regulations is notoriously difficult. Regulatory agencies often lack information on compliance and the ability to effectively punish or sanction violators. In our recent scalable deep learning study to identify brick kilns and aid regulatory capacity, we demonstrate an accurate, scalable machine-learning approach for identifying brick kilns, a highly polluting informal industry in Bangladesh, in satellite imagery. Our approach identifies kilns with 94.2% accuracy and 88.7% precision and extracts the precise GPS coordinates of every brick kiln across Bangladesh. This solution offers a low-cost, replicable method for regulatory agencies to generate information on key pollution sources."
–Marshall Burke, Associate Professor, Doerr School of Sustainability, and Deputy Director, Center on Food Security and the Environment

3 Sustainability and AI
Informing Environmental Policy

Continued

EYE ON CAMPUS

- Deep Learning With Satellite Imagery to Enhance Environmental Enforcement
- Detecting Environmental Violations With Satellite Imagery in Near Real Time
- Scalable Deep Learning to Identify Brick Kilns and Aid Regulatory Capacity
- ForestNet: Classifying Drivers of Deforestation in Indonesia Using Deep Learning on Satellite Imagery
- METER-ML: A Multi-Sensor Earth Observation Benchmark for Automated Methane Source Mapping
- The Changing Risk and Burden of Wildfire in the United States
- On the Opportunities and Risks of Foundation Models (Environment Section 5.3)
- AI's Carbon Footprint Problem
- Using Machine Learning to Analyze Physical Causes of Climate Change: A Case Study of U.S. Midwest Extreme Precipitation

4 Sustainability and AI
Managing the Built Environment

★ WHAT'S NEW?

Stanford researchers are using machine learning to make infrastructure more adaptive and efficient. By training models with enough data, we can **understand the unique demand patterns of individual buildings**, which allows us to reduce and optimize their infrastructure use. This work is applicable to any entity managing multiple building operations, including corporate campuses. Our urban informatics lab at Stanford focuses on addressing sustainability challenges in the built environment, from individual buildings to entire cities. A framework that combines a network-based machine learning algorithm with engineering simulation can more accurately **predict how buildings consume energy at different scales and times**. This approach can help us design more sustainable cities.

In order to promote urban sustainability and walkability, Stanford scientists are using a deep learning-based computer vision model to identify changes in marked crosswalks around more than 4,000 US transit stations over a 14-year period. This approach could potentially be used in the future to **automatically detect large-scale infrastructure changes** at a reasonable cost.

In addition to optimizing design and energy use, researchers at Stanford are using data-driven methods to **integrate nature into the built environment** by understanding how nature is tied to human health.

"People in many countries spend around 90% of their time in buildings, making the physical and digital design of these environments a powerful means of studying, shaping, and supporting human behavior and wellbeing. To best support human well-being, it is imperative that we increase understanding of how attributes like connection to nature and access to natural light, affect well-being outcomes such as stress, creativity, cognitive functioning and pro-environmental behavior. In collaboration with James Landay (Professor of Computer Science, Stanford University), our team is developing an extensible platform that integrates information from environmental sensors, personal devices, and experience sampling interfaces. We are deploying this platform in the wild to capture ecologically valid data about the status of workers and the spaces they occupy both in office and home workspaces."

–Sarah Billington, UPS Foundation Professor, Civil and Environmental Engineering, and Senior Fellow, Stanford Woods Institute for the Environment

4 Sustainability and AI
Managing the Built Environment

Continued

WHY DOES THIS MATTER NOW?

Buildings contribute approximately 40% of global emissions[1]. Of this, about 27% are related to building operations, while the remaining 13% come from embodied emissions from the construction of buildings[1]. Reducing these emissions is crucial for mitigating climate change and creating a more sustainable future. Buildings are growing older, with the average age of structures in cities like New York being over 50 years[2]. Thus, in addition to prioritizing new energy-efficient design, we need to focus on existing, older buildings. Buildings tend to get disconnected from power to preserve essential operations during extreme weather events, hence incorporating resilience in building operations by adjusting power use is becoming increasingly more important. As explained in the Decarbonizing Energy Systems section of this brief, power outages are estimated to cost between 10 and 100 billion dollars annually[3]. The insight we are gaining predicting urban-scale energy consumption at hourly, daily, and monthly intervals can inform decision-making of a wide range of urban sustainability stakeholders, such as architects, engineers, and policymakers.

Beyond energy impacts, the design and operations of the built environment dramatically impact human physical and mental health. Health implications vary dramatically depending on one's postcode with, for example, urban heat islands becoming more prevalent due to climate change[4]. Therefore, we need to prioritize insulation and incorporate more greenery in our built environment. Recent research shows the impact of nature on our mental health[5]. As we spend more time indoors and in urban areas, designing buildings and cities that include elements of nature can be transformational to human well-being.

"Enhancing the energy efficiency of commercial buildings is a challenging problem, due to the fact that centralized building systems—such as heating, ventilation and air conditioning (HVAC), or lighting—must be synthesized and integrated with individual inhabitant behavior and energy consumption patterns. This motivates our research to design, analyze, and test a cyber-physical and human-in-the-loop enabled control system that can drive sustained energy savings and enable dynamic interactions between occupants in commercial buildings. It brings together expertise in computational building science, network theory, data science, and control systems to integrate physical building information and inhabitants with cyber (building-human) interaction models to enable intelligent control of commercial building systems. We aim to achieve this via an integrated cyber-physical system (CPS), called Building Information, Inhabitant, Interaction, Intelligent Integrated Modeling (BI5M), aimed at reducing energy usage and enhancing collaboration in buildings."

–Rishee Jain, Assistant Professor of Civil & Environmental Engineering and Director of the Stanford Urban Informatics Lab (UIL)

4 Sustainability and AI
Managing the Built Environment

Continued

Read more:

1 Buildings – Analysis, International Energy Agency

2 Average Age of Infrastructure, Statista

3 Surging Weather-Related Power Outages and Surging Power Outages and Climate Change, Climate Central

4 Heat Islands and Equity, EPA

5 Building nature into cities for better mental health, Stanford News

EYE ON CAMPUS

HAI RESEARCH

- Marked Crosswalks in US Transit-Oriented Station Areas, 2007–2020: A Computer Vision Approach Using Street View Imagery
- Unlocking Demand Response in Commercial Buildings: Empirical Response of Commercial Buildings to Daily Cooling Set Point Adjustments
- Data-driven Urban Energy Simulation (DUE-S): A framework for integrating engineering simulation and machine learning methods in a multi-scale urban energy modeling workflow - ScienceDirect
- Physical workplaces and human well-being: A mixed-methods study to quantify the effects of materials, windows, and representation on biobehavioral outcomes

5 Sustainability and AI
Engaging with our Environment through VR/AR

★ WHAT'S NEW?

Along with traditional metrics and methods to assess sustainability, many industries are examining the future of their businesses and how they can continue to meet client needs while improving the sustainability of their methods using emerging technologies such as the metaverse, Virtual Reality (VR), Augmented Reality (AR) and Web 3.0. This includes designing cheaper what-if scenarios to span more potential situations. Several industries, including design, are considering VR as a solution to some of these issues. For example, VR for architecture can help promote sustainability by offering digital solutions. Through the use of a head-mounted display (HMD), hand controllers, and stereoscopic sound, immersive virtual reality (IVR) technologies **provide a vivid first-person experience in a 3D virtual environment** augmented with multisensory feedback. IVR allows users to perceive with multiple senses as if they were in the real world (so-called psychological presence).

Many IVR research projects investigate how virtual experiences could **improve climate change engagement**. Research on the impact of immersive virtual environments for environmental literacy is still in its infancy. Being environmentally literate requires knowledge of earth science along with the intention and motivation to act. There is promising potential for these technologies to **shift human behavior to being environmentally responsible** with the aim of solving current environmental issues and preventing new ones.

"VR experiences can help people understand climate science. First, VR tools can mark the progression of ecological systems affected by climate change and increase participant interest, concern, or knowledge about the issue. Climate change research in VR can also expose users to new experiences that would otherwise be impossible (e.g., people cannot accelerate time to see climate change effects), counterproductive (e.g., people should not burn fossil fuels to demonstrate heat being trapped in the atmosphere), costly (e.g., traveling to an area affected by climate change also harms the environment), or dangerous (e.g., wildfire training in-person can risk lives, whereas training in VR does not) in the physical world. VHIL research shows that VR can deliver meaningful climate change content and test how people think, feel, and respond to the issues."

-Jeremy N. Bailenson, Founding Director of Stanford University's Virtual Human Interaction Lab and Professor of Communication

5 Sustainability and AI

Engaging with our Environment through VR/AR

Continued

"Virtual Reality (VR) opens the window to connect people's emotions to future climate scenarios through simulations that immerse the senses and bring these scenarios psychologically and emotionally close. As emotions play an essential role in climate change engagement, with VR, we don't need to wait for the climate consequences to allow people to feel them, and engage in mitigation and adaptation behaviors. Leveraging our research at VHIL on the impact of VR design on climate change behavior, artificial intelligence (AI) can help understand it better and customize VR experiences to make the experiences more personal, increasing the user's connection to the environment."

-Anna C. Queiroz, Postdoc researcher at the Virtual Human Interaction Lab, Stanford University

WHY DOES THIS MATTER NOW?

One of the biggest barriers to climate and sustainability action is the distance, both in time and space, between our actions and their consequences. This leads to a psychological disconnect. As one of the fastest growing industries with over 32% compounded annual growth rate[1], AR/VR adoption can help bridge that distance. These technologies increase access to information, knowledge, and nontraditional experiences to users and researchers around the world. An important characteristic of digital technology is its multimodal ability to include texts, images, animations, sound, and even haptic feedback to create rich and engaging experiences through a steadily growing supply of interactive applications. By enabling users to visualize something that would otherwise be invisible to them, digital technologies make it possible to engage with environmental issues in more specific and interactive ways.

Read more:

1 IDC Spending Guide Forecasts Strong Growth for Augmented and Virtual Reality

EYE ON CAMPUS

- Virtual Reality as a Promising Tool to Promote Climate Change Awareness
- Using Virtual Reality in Sea Level Rise Planning and Community Engagement—An Overview
- The Stanford Ocean Acidification Experience
- Experiencing Nature: Embodying Animals in Immersive Virtual Environments Increases Inclusion of Nature in Self and Involvement With Nature
- Short- and Long-Term Effects of Embodied Experiences in Immersive Virtual Environments on Environmental Locus of Control and Behavior
- The Impact of Vivid Messages on Reducing Energy Consumption Related to Hot Water Use
- Do Students Learn Better with Immersive Virtual Reality Videos than Conventional Videos? A Comparison of Media Effects with Middle School Girls

Industry Take

Industry plays a critical role in creating and scaling novel applications of AI in sustainability. It is, therefore, a goal and privilege of HAI to convene stakeholders from industry in addition to those in academia, government, and civil society to address the technical and societal challenges posed by AI in various sustainability problems. Leading venture investors, positioned at the frontlines of startup innovation in robotics, can provide a unique perspective on the impact and role of AI technologies in sustainability assessment and management problems.

Industry Take

"Many of the most promising climate technology startups leverage a robust understanding of natural and human systems, and AI is a critical enabler of such understanding. For instance, AI-based approaches can unlock decarbonization in the built environment by allowing building owners to optimize energy demand from HVAC and cooling systems, develop robust plans to reduce operational and embedded carbon, and efficiently procure distributed energy resources for their sites. AI can also enhance the ability to plan for adaptation and resilience in the face of physical climate risks like floods and fires, by analyzing ocean salinity data, Earth observation data, and published climate science at scale. With AI, we can significantly reduce carbon emissions during the decisive decade while planning for the changes that will result from a warming planet."
–Emily Kirsch, Founder and Managing Partner, Powerhouse Ventures

"We recognize many applications for AI in accelerating the decoupling of economic growth from pollution and species extinction. Among other examples, we're already seeing AI enable remarkable efficiency in optimizing industrial processes, supply chains, building operations, averting energy waste, and commensurate carbon emissions. AI is augmenting biotech and materials science to enable more sustainable production of food and novel materials. Furthermore, AI is already enabling better decision-making regarding the physical risks of climate change and enabling better preparation and ongoing risk reduction as society recognizes both the imperative and the opportunity in creating a definitively sustainable economy."
–Sierra Peterson, Founding Partner, Voyager

"Mitigating climate change is the most important work of our lifetime. To do so requires transforming our physical economy. We will need solutions based in hardware, biology, and chemical innovations to draw carbon out of the air, enable us to store intermittently generated renewable power, and more. But we also need huge amounts of data, compute, and intelligence to help us turbo-charge those efforts. Some of the most meaningful opportunities for AI in climate are high-throughput discovery and screening of next-generation, low-carbon products; data-driven rollout of decarbonization tools like renewable energy; and real-time optimization of complex assets and systems, such as the grid."
–Sam Smith-Eppsteiner, Partner at Innovation Endeavors

"The next decade is the most important for climate change. It is the turning point for us retooling and rebooting the entire world's energy system. As the grid shifts from centralized, predictable generation to distributed, unpredictable renewable energy and storage, and as the demands on the grid massively increase given electrification of transportation and heating, AI systems to manage and orchestrate this elaborate dance will become critical to humanity's ability to decarbonize."
–Greg Smithies, Partner & Co-Head of the Climate Technology Investment Team at Fifth Wall

Philanthropy Take

"Climate solutions and artificial intelligence are intrinsically linked. Predictive rebalancing of microgrids, decision support for precision agriculture, and modeling complex data streams to identify the highest impact decarbonization pathways all require deep expertise in the physical world and access to transformative computational technologies. This field of sustainability and AI, still in its infancy, could be responsible for humanity's successful future on planet Earth and requires our committed engagement as scientists, policymakers, philanthropists, and entrepreneurs."
–Vilas Dhar, President, Patrick J. McGovern Foundation, HAI Advisory Council

"AI enables the kind of rapid iteration and experimentation in the physical sciences that has previously only been possible in computing. For key technologies like long duration energy storage, low carbon materials and efficient transportation, progress depends on breakthroughs in everything from biology to materials science. We need newly optimized enzymes, better battery chemistries and more efficient membranes, and AI is accelerating that exploration and discovery process."
–Mike Schroepfer, Climate Tech Investor and Philanthropist

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Industry Brief

CORPORATE
ENGAGEMENT

Corporate Engagement

Stanford HAI seeks corporate members who will enable it to lead with the unparalleled interdisciplinary breadth and excellence of Stanford University, and a laser focus on human-centered development and deployment of AI technology. We invite engagement from companies that share our mission to advance AI research, education, policy, and practice to improve the human condition.

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Industry Brief

CORPORATE ENGAGEMENT

Are you prepared for the next wave of change?

Things you should know.

Using AI for environmental applications could:

Contribute
$5.2
TRILLION USD
to the global economy in 2030, a 4.4% increase relative to business as usual

Create
38.2
MILLION
net new jobs across the global economy

Reduce worldwide GHG emissions by 4% in 2030, an amount equivalent to
2.4 GT CO2E –

Source: How AI can enable a sustainable future Estimating the economic and emissions impact of AI adoption in agriculture, water, energy and transport.

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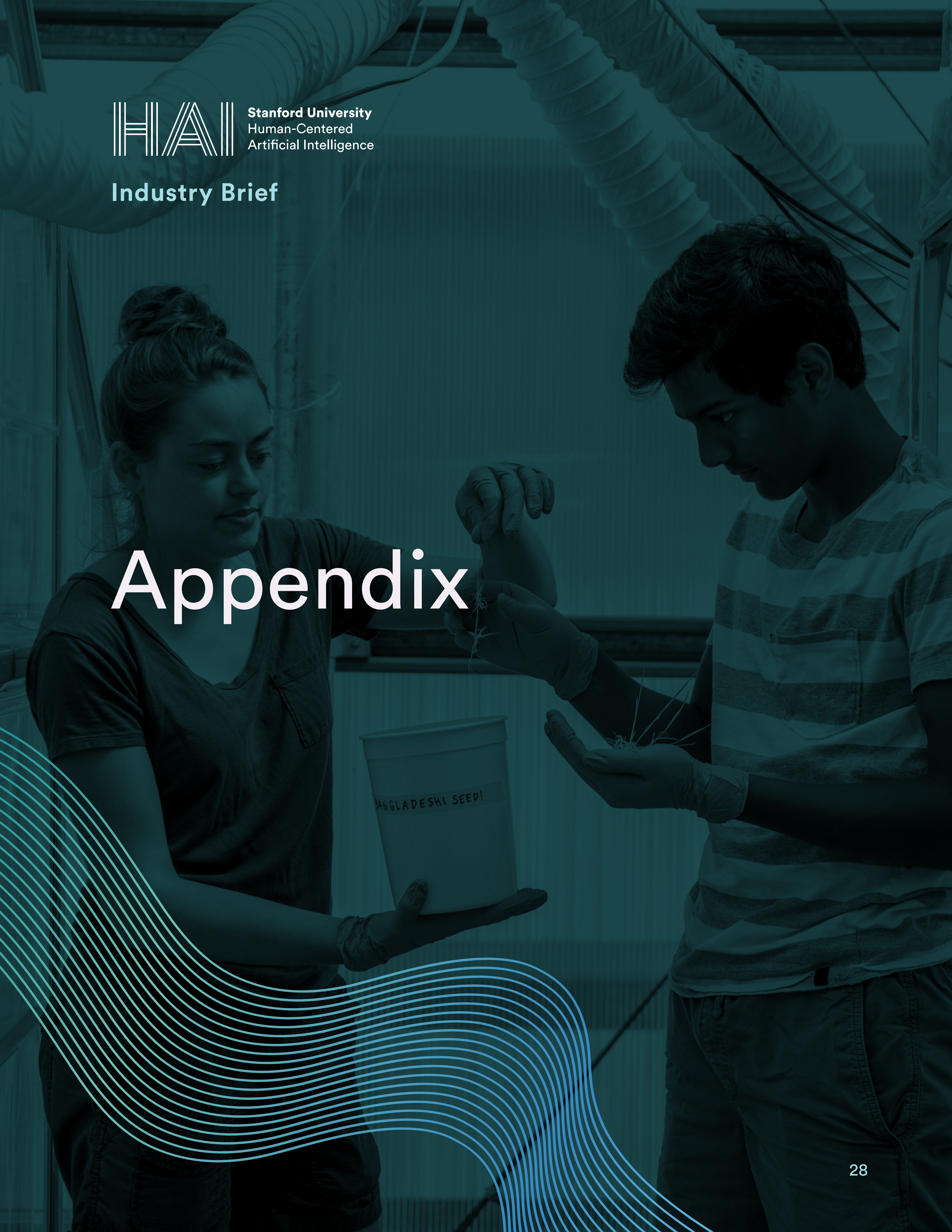
Become a corporate member today.

50% of companies are likely to miss the window of opportunity.[1] Let's talk.

Learn more about the Corporate Members Program and the Stanford advantage.

Panos Madamopoulos,
Managing Director for Industry Programs and Partnerships

1 Jacques Bughin, "Wait-and-See Could Be a Costly AI Strategy," MIT Sloan Management Review, June 15, 2018.



Appendix

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Artificial Intelligence Definitions

Intelligence might be defined as the ability to learn and perform a range of techniques to solve problems and achieve goals—techniques that are appropriate to the context in an uncertain, ever-varying world. A fully pre-programmed factory robot is flexible, accurate, and consistent, but not intelligent.

Artificial Intelligence (AI), is a term coined in 1955 by John McCarthy, Stanford's first faculty member in AI, who defined it as "the science and engineering of making intelligent machines." Much research has human program software agents with the knowledge to behave in a particular way, like playing chess, but today, we emphasize agents that can learn, just as human beings navigating our changing world.

Autonomous systems can independently plan and decide sequences of steps to achieve a specified goal without being micromanaged. A hospital delivery robot must autonomously navigate busy corridors to succeed in its task. In AI, autonomy doesn't have the sense of being self-governing common in politics or biology.

Machine Learning (ML) is the part of AI that studies how computer systems can improve their perception, knowledge, decisions, or actions based on experience or data. For this, ML draws from computer science, statistics, psychology, neuroscience, economics, and control theory.

In **supervised learning**, a computer learns to predict human-given labels, such as particular dog breeds based on labeled dog pictures. **Unsupervised learning** does not require labels, but sometimes adopts **selfsupervised learning**, constructing its own prediction tasks such as trying to predict each successive word in a sentence. **Reinforcement learning** enables autonomy by allowing an agent to learn action sequences that optimize its total rewards, such as winning games, without explicit examples of good techniques.

Deep Learning is the use of large multi-layer **(artificial) neural networks** that compute with continuous (real number) representations, similar to the hierarchically organized neurons in human brains. It is successfully employed for all types of ML, with better generalization from small data and better scaling to big data and compute budgets. A recent breakthrough is the **transformer**, a neural net architecture which flexibly incorporates context via an attention mechanism, allowing powerful and computationally efficient analysis and generation of sequences, such as words in a paragraph.

Foundation models are an emerging class of models, often transformers trained by self-supervision on large-scale broad data, that can be easily adapted to perform a wide range of downstream tasks. The best-known examples are large pretrained language models like GPT-3, but the term extends to models for all modalities of data and knowledge.

An **algorithm** is a precise list of steps to take, such as a computer program. AI systems contain algorithms, but typically just for a few parts like a learning or reward calculation method. Much of their behavior emerges via learning from data or experience, a fundamental shift in system design that Stanford alumnus Andrej Karpathy dubbed **Software 2.0**.

Narrow AI is intelligent systems for particular tasks, e.g., **speech** or **facial recognition**. **Human-level AI**, or **artificial general intelligence (AGI)**, seeks broadly intelligent, context-aware machines. It is needed for effective, adaptable **social chatbots** or **human-robot interaction**.

Human-Centered Artificial Intelligence is AI that seeks to augment the abilities of, address the societal needs of, and draw inspiration from human beings. It researches and builds effective partners and tools for people, such as a robot helper and companion for the elderly.

Text by Professor Christopher Manning, v 1.2, April 2022

References

Sustainability and AI

Decarbonizing Energy Systems

de Chalendar, J. A., & Benson, S. M. (2021). A physics-informed data reconciliation framework for real-time electricity and emissions tracking. *Applied Energy*, 304, 117761. https://doi.org/10.1016/j.apenergy.2021.117761

de Chalendar, J. A., Taggart, J., & Benson, S. M. (2019). Tracking emissions in the US electricity system. *Proceedings of the National Academy of Sciences*, 116(51), 25497–25502. https://doi.org/10.1073/pnas.1912950116

Deng, H. D., Zhao, H., Jin, N., Hughes, L., Savitzky, B. H., Ophus, C., Fraggedakis, D., Borbély, A., Yu, Y.-S., Lomeli, E. G., Yan, R., Liu, J., Shapiro, D. A., Cai, W., Bazant, M. Z., Minor, A. M., & Chueh, W. C. (2022). Correlative image learning of chemo-mechanics in phase-transforming solids. *Nature Materials, 21*(5), Article 5. https://doi.org/10.1038/s41563-021-01191-0

Mern, J., & Caers, J. (2022). Intelligent prospector v1.0: Geoscientific model development and prediction by sequential data acquisition planning with application to mineral exploration. *Geoscientific Model Development Discussions*, 1–50. https://doi.org/10.5194/gmd-2022-166

Sheng, H., Irvin, J., Munukutla, S., Zhang, S., Cross, C., Story, K., Rustowicz, R., Elsworth, C., Yang, Z., Omara, M., Gautam, R., Jackson, R. B., & Ng, A. Y. (2020). *OGNet: Towards a Global Oil and Gas Infrastructure Database using Deep Learning on Remotely Sensed Imagery* (arXiv:2011.07227). arXiv. https://doi.org/10.48550/arXiv.2011.07227

Wang, J., Tchapmi, L. P., Ravikumar, A. P., McGuire, M., Bell, C. S., Zimmerle, D., Savarese, S., & Brandt, A. R. (2020). Machine vision for natural gas methane emissions detection using an infrared camera. *Applied Energy*, 257, 113998. https://doi.org/10.1016/j.apenergy.2019.113998

Yu, J., Wang, Z., Majumdar, A., & Rajagopal, R. (2018). DeepSolar: A Machine Learning Framework to Efficiently Construct a Solar Deployment Database in the United States. *Joule, 2*(12), 2605–2617. https://doi.org/10.1016/j.joule.2018.11.021

Zelikman, E., Zhou, S., Irvin, J., Raterink, C., Sheng, H., Avati, A., Kelly, J., Rajagopal, R., Ng, A. Y., & Gagne, D. (2020). *Short-Term Solar Irradiance Forecasting Using Calibrated Probabilistic Models* (arXiv:2010.04715). arXiv. https://doi.org/10.48550/arXiv.2010.04715

Zhou, S., Irvin, J., Wang, Z., Zhang, E., Aljubran, J., Deadrick, W., Rajagopal, R., & Ng, A. (n.d.). *DeepWind: Weakly Supervised Localization of Wind Turbines in Satellite Imagery*.

Zhu, B., Lui, N., Irvin, J., Le, J., Tadwalkar, S., Wang, C., Ouyang, Z., Liu, F. Y., Ng, A. Y., & Jackson, R. B. (2022). *METER-ML: A Multi-Sensor Earth Observation Benchmark for Automated Methane Source Mapping* (arXiv:2207.11166). arXiv. https://doi.org/10.48550/arXiv.2207.11166

Accelerating Sustainable Agriculture

Behrer, A. P., & Lobell, D. (2022). Higher levels of no-till agriculture associated with lower PM2.5 in the Corn Belt. *Environmental Research Letters*, 17(9), 094012. https://doi.org/10.1088/1748-9326/ac816f

Burke, M., & Lobell, D. B. (2017). Satellite-based assessment of yield variation and its determinants in smallholder African systems. *Proceedings of the National Academy of Sciences*, 114(9), 2189–2194. https://doi.org/10.1073/pnas.1616919114

Deines, J. M., Wang, S., & Lobell, D. B. (2019). Satellites reveal a small positive yield effect from conservation tillage across the US Corn Belt. *Environmental Research Letters*, 14(12), 124038. https://doi.org/10.1088/1748-9326/ab503b

Lobell, D. B., Di Tommaso, S., & Burney, J. A. (2022). Globally ubiquitous negative effects of nitrogen dioxide on crop growth. *Science Advances, 8*(22), eabm9909. https://doi.org/10.1126/sciadv.abm9909

Rustowicz, R. M., Cheong, R., Wang, L., Ermon, S., Burke, M., & Lobell, D. (n.d.). *Semantic Segmentation of Crop Type in Africa: A Novel Dataset and Analysis of Deep Learning Methods.* 8.

Wang, Y., Zechner, M., Mern, J. M., Kochenderfer, M. J., & Caers, J. K. (2022). A sequential decision-making framework with uncertainty quantification for groundwater management. *Advances in Water Resources*, 166, 104266. https://doi.org/10.1016/j.advwatres.2022.104266

Hartmann, W.. Satellite Imagery, AI and Efficiency in Agricultural Water Use. *Retrieved December 20, 2022*, from http://web.stanford.edu/~wesleyr/AgWater.html

You, J., Li, X., Low, M., Lobell, D., & Ermon, S. (2017). Deep Gaussian Process for Crop Yield Prediction Based on Remote Sensing Data. *Proceedings of the AAAI Conference on Artificial Intelligence, 31*(1). https://doi.org/10.1609/aaai.v31i1.11172

Informing Environmental Policy

Bommasani, R., Hudson, D. A., Adeli, E., Altman, R., Arora, S., von Arx, S., Bernstein, M. S., Bohg, J., Bosselut, A., Brunskill, E., Brynjolfsson, E., Buch, S., Card, D., Castellon, R., Chatterji, N., Chen, A., Creel, K., Davis, J. Q., Demszky, D., … Liang, P. (2022). *On the Opportunities and Risks of Foundation Models* (arXiv:2108.07258). arXiv. http://arxiv.org/abs/2108.07258

References

Sustainability and AI

Burke, M., Driscoll, A., Heft-Neal, S., Xue, J., Burney, J., & Wara, M. (2021). The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences, 118*(2), e2011048118. https://doi.org/10.1073/pnas.2011048118

Chugg, B., Rothbacher, N., Feng, A., Long, X., & Ho, D. E. (2022). Detecting Environmental Violations with Satellite Imagery in Near Real Time: Land Application under the Clean Water Act. *Proceedings of the 31st ACM International Conference on Information & Knowledge Management*, 3052–3062. https://doi.org/10.1145/3511808.3557104

Davenport, F. V., & Diffenbaugh, N. S. (2021). Using Machine Learning to Analyze Physical Causes of Climate Change: A Case Study of U.S. Midwest Extreme Precipitation. *Geophysical Research Letters*, 48(15), e2021GL093787. https://doi.org/10.1029/2021GL093787

Handan-Nader, C., & Ho, D. E. (2019). Deep learning to map concentrated animal feeding operations. *Nature Sustainability*, 2(4), 298–306. https://doi.org/10.1038/s41893-019-0246-x

Handan-Nader, C., Ho, D. E., & Liu, L. Y. (2021). Deep learning with satellite imagery to enhance environmental enforcement. *In Data Science Applied to Sustainability Analysis* (pp. 205–228). Elsevier. https://doi.org/10.1016/B978-0-12-817976-5.00011-5

Irvin, J., Sheng, H., Ramachandran, N., Johnson-Yu, S., Zhou, S., Story, K., Rustowicz, R., Elsworth, C., Austin, K., & Ng, A. Y. (2020). *ForestNet: Classifying Drivers of Deforestation in Indonesia using Deep Learning on Satellite Imagery* (arXiv:2011.05479). arXiv. https://doi.org/10.48550/arXiv.2011.05479

Lee, J., Brooks, N. R., Tajwar, F., Burke, M., Ermon, S., Lobell, D. B., Biswas, D., & Luby, S. P. (2021). Scalable deep learning to identify brick kilns and aid regulatory capacity. *Proceedings of the National Academy of Sciences*, 118(17), e2018863118. https://doi.org/10.1073/pnas.2018863118

Zhu, B., Lui, N., Irvin, J., Le, J., Tadwalkar, S., Wang, C., Ouyang, Z., Liu, F. Y., Ng, A. Y., & Jackson, R. B. (2022). *METER-ML: A Multi-Sensor Earth Observation Benchmark for Automated Methane Source Mapping* (arXiv:2207.11166). arXiv. https://doi.org/10.48550/arXiv.2207.11166

Managing the Built Environment

de Chalendar, J. A., McMahon, C., Fuentes Valenzuela, L., Glynn, P. W., & Benson, S. M. (2023). Unlocking demand response in commercial buildings: Empirical response of commercial buildings to daily cooling set point adjustments. *Energy and Buildings*, 278, 112599. https://doi.org/10.1016/j.enbuild.2022.112599

Douglas, I. P., Murnane, E. L., Bencharit, L. Z., Altaf, B., Costa, J. M. dos R., Yang, J., Ackerson, M., Srivastava, C., Cooper, M., Douglas, K., King, J., Paredes, P. E., Camp, N. P., Mauriello, M. L., Ardoin, N. M., Markus, H. R., Landay, J. A., & Billington, S. L. (2022). Physical workplaces and human well-being: A mixed-methods study to quantify the effects of materials, windows, and representation on biobehavioral outcomes. *Building and Environment*, 224, 109516. https://doi.org/10.1016/j.buildenv.2022.109516

Li, M., Sheng, H., Irvin, J., Chung, H., Ying, A., Sun, T., Ng, A. Y., & Rodriguez, D. A. (2022). Marked crosswalks in US transit-oriented station areas, 2007–2020: A computer vision approach using street view imagery. *Environment and Planning B: Urban Analytics and City Science*, 23998083221112156. https://doi.org/10.1177/23998083221112157

Nutkiewicz, A., Yang, Z., & Jain, R. K. (2018). Data-driven Urban Energy Simulation (DUE-S): A framework for integrating engineering simulation and machine learning methods in a multi-scale urban energy modeling workflow. *Applied Energy*, 225, 1176–1189. https://doi.org/10.1016/j.apenergy.2018.05.023

Engaging with our Environment through VR/AR

Ahn, S. J. G., Bostick, J., Ogle, E., Nowak, K. L., McGillicuddy, K. T., & Bailenson, J. N. (2016). Experiencing Nature: Embodying Animals in Immersive Virtual Environments Increases Inclusion of Nature in Self and Involvement With Nature: EMBODYING ANIMALS IN IMMERSIVE VIRTUAL ENVIRONMENTS. *Journal of Computer-Mediated Communication*, 21(6), 399–419. https://doi.org/10.1111/jcc4.12173

Ahn, S. J. (Grace), Bailenson, J. N., & Park, D. (2014). Short- and long-term effects of embodied experiences in immersive virtual environments on environmental locus of control and behavior. *Computers in Human Behavior*, 39, 235–245. https://doi.org/10.1016/j.chb.2014.07.025

Bailey, J. O., Bailenson, J. N., Flora, J., Armel, K. C., Voelker, D., & Reeves, B. (2015). The Impact of Vivid Messages on Reducing Energy Consumption Related to Hot Water Use. *Environment and Behavior*, 47(5), 570–592. https://doi.org/10.1177/0013916514551604

Calil, J., Fauville, G., Queiroz, A. C. M., Leo, K. L., Mann, A. G. N., Wise-West, T., Salvatore, P., & Bailenson, J. N. (2021). Using Virtual Reality in Sea Level Rise Planning and Community Engagement—An Overview. *Water*, 13(9), Article 9. https://doi.org/10.3390/w13091142

Fauville, G., Queiroz, A. C. M., & Bailenson, J. N. (2020). Virtual reality as a promising tool to promote climate change awareness. In *Technology and Health* (pp. 91–108). Elsevier. https://doi.org/10.1016/B978-0-12-816958-2.00005-8

Queiroz, A. C. M., Fauville, G., Herrera, F., Leme, M. I. D. S., & Bailenson, J. N. (2022). Do Students Learn Better With Immersive Virtual Reality Videos Than Conventional Videos? A Comparison of Media Effects With Middle School Girls. *Technology, Mind, and Behavior, 3*(3).

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Brief Author & Editor

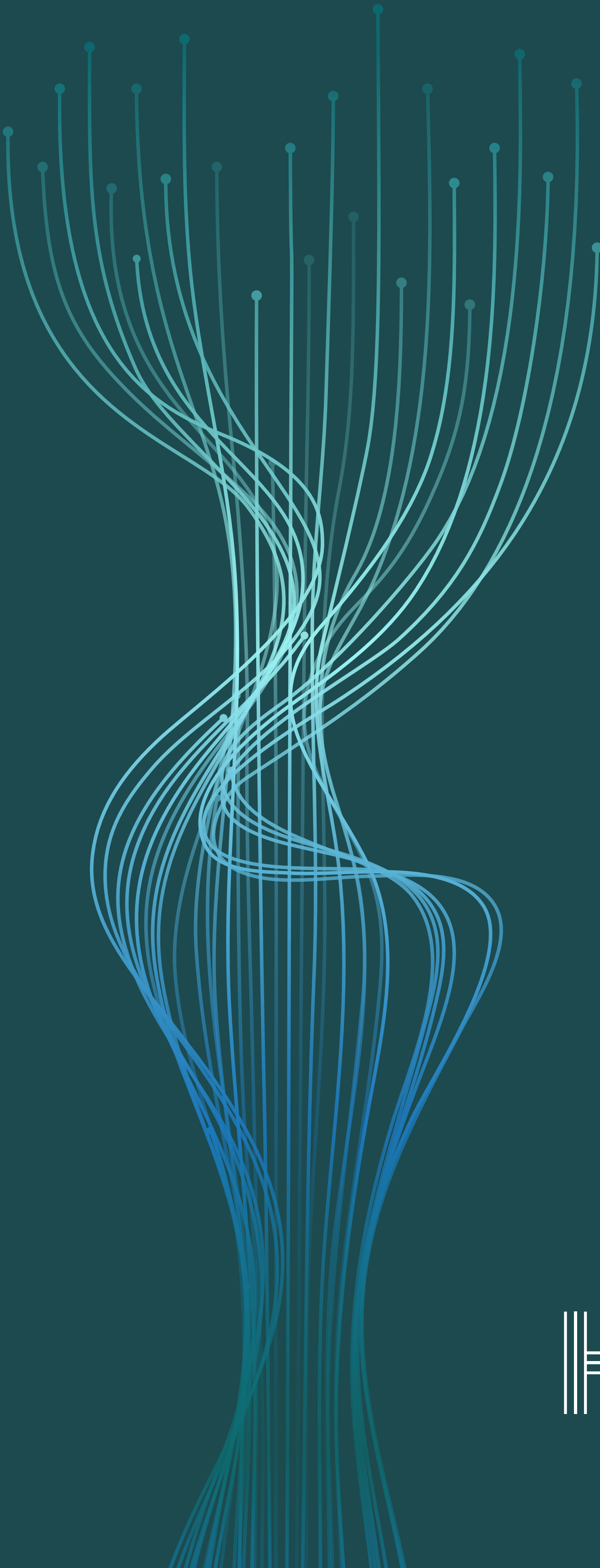
Christina Baladis
Joint MS-MBA, Stanford Graduate School of Business, and Emmett-Interdisciplinary Program in Environment and Resources, Doerr School of Sustainability

Follow-up Requests

For research collaborations or questions about the technical content of this brief, please reach out to Ahmad Rushdi, Senior Research Manager, Stanford HAI. For partnerships, please reach out to Panos Madamopoulos, Managing Director for Industry Programs and Partnerships, Stanford HAI.

Acknowledgments

This brief was produced by the HAI Industry Programs & Partnerships team as one of its strategic initiatives. Research and writing were led by Christina Baladis and Ahmad Rushdi in coordination with Marc Gough, Victoria Moore, and Panos Madamopoulos. We are grateful for the generosity of the following people for providing their time, helpful suggestions, and constructive feedback in the creation of this brief (names listed in no particular order): Jacques de Chalendar, Pamela Matson, Jef Caers, Peter Henderson, Stefano Ermon, David Lobell, Daniel E. Ho, Marshall Burke, Sarah Billington, Rishee Jain, Jeremy N. Bailenson, Anna C. Queiroz, Alex Pentland, Emily Kirsch, Sierra Peterson, Sam Smith-Eppsteiner, Greg Smithies, Vilas Dhar and Mike Schroepfer. We would also like to thank the HAI staff team including Vanessa Parli, Jeanina Casusi, Joe Hinman, Shana Lynch, Stacy Peña, and Michi Turner for their help preparing the publication.



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