When preparing for a March 2007 talk at the US National Science Foundation (NSF), I searched the Web for scholarly work on AI and climate change, the natural environment, and sustainability. My search was not exhaustive, largely based on keywords, but it wasn’t trivial either. Still, little turned up in the intersection of AI and sustainability in early 2007, and most of what did, as I recall, was in environmental science publications and appeared to be dominated by European researchers using evolutionary computation for the purposes of optimization.¹

AI and sustainability has grown substantially in the last few years. To some extent, this tracks with increasing interest in sustainability and computing more generally. However, AI is helping to drive this larger movement, rather than simply riding along. Indeed, it’s hard to imagine that AI would not be central to understanding and managing the great complexity of maintaining a healthy planet in the face of pervasive and transformative human activity.

A visible and scientifically significant landmark in this growth of AI and sustainability is the establishment of the Computational Sustainability Institute,² with its focus on AI and many sustainability areas, such as biodiversity and alternative energy. The institute grew from a 2008 Expedition in Computing Award from the NSF to Cornell University, Oregon State University, Bowdoin College, Howard University, and other partners, quickly attracting other researchers, educators, government, and industry. The first conference on computational sustainability took place in 2009, followed by a second in 2010 and leading in 2011 to a special track on Computational Sustainability at the Association for the Advancement of Artificial Intelligence (AAAI) conference.

Coinciding with the institute’s founding was a groundswell of activity to include sustainability tracks at other AI-related conferences. Machine learning and data mining have been strong among these, and in 2010, a second sustainability-focused Expedition in Computing award was given to the University of Minnesota and its partners for data-driven understanding of climate change and related phenomena.

Forthcoming articles in this new IEEE Intelligent Systems AI and Sustainability Department will elaborate on AI’s deployment in many areas of sustainability as well as the challenges and opportunities that sustainability issues bring to AI research, education, and practice. This opening article will touch upon the main themes at the intersection of AI and sustainability, but it will primarily concentrate on the larger contexts of sustainability, and on computing and sustainability, thereby setting the stage for articles to come.

**Sustainability**

The United Nations’ Bruntland report contains a popular and succinct definition of sustainability: “Sustainable development is development that meets the needs of the present
without compromising the ability of future generations to meet their own needs.”

To many, the phrase “sustainable development” is an oxymoron, but the “needs” spoken of in the Bruntland report are not about the luxuries of the materially wealthy, but rather about the survival needs of the poor and starving. As contextualized in the report, “development” is about bringing all those on the planet up to a reasonable standard of living, rather than on those who are already using plenty. Indeed, there is a nascent AI for Development Group actively exploring AI’s role in advancing social equity, together with a larger computing for development group.

More generally, the reference to “needs” begs the question as to exactly what these are, both now and in the future. Achieving and then maintaining safe and adequate water, food, air, and other health-related criteria for all people are high-level goals. When we work backward from these ultimate human-centric goals, we arrive at a large number of sustainability desiderata relating to biodiversity, energy, toxins, climate change, disease, community planning, agriculture, emergency response, transportation, garbage, materials, economics, policy, and human behavior, among others. An expansion of what is a many-node and densely connected graph will define the purview of the IEEE Intelligent Systems’ AI and Sustainability area. Readers are encouraged to trace out what they imagine this graph looks like from their own perspective and to ask students at all levels to do so as well. What we desire to be sustained shouldn’t be simply enumerated for people; it should be a focus of deep, ongoing conversation.

Sustainability has received mixed attention from academics, governments, and industries over the past few decades. As the Brundtland report indicates, many have sounded the alarm for a good long time. Silent Spring, Rachel Carson’s book on environmental poisoning through pesticides and the like was published in 1962. It is often credited for an environmental awakening, but one that has waxed and waned over the years. The first scientific reports on rising CO2 levels and the implications for warming the planet were published by the early 1960s, reaching levels of scientific consensus by the 1980s.

Nevertheless, a significant (but minority) proportion of Americans, to take but one nation, aren’t simply skeptics, but are dismissive and easily shifted—the materially wealthy world in general has been slow to react. So we have to wonder whether the new initiatives will have staying power, and having staying power through this and all subsequent generations is critical, at least if we view the planet from the perspective of the human time scales of decades, centuries, and millennia.

In the US, a new NSF initiative—at fully 10 percent of the NSF’s proposed budget for the upcoming fiscal year—will support science, engineering, and education for sustainability. The SEES initiative follows a host of discipline-focused programs, but now the emphasis is squarely on the need for strong interdisciplinary partnerships leading to a science of sustainability. The Proceedings of the National Academy of Sciences launched a sustainability science section and academic departments and schools of sustainability are springing up.

It is striking, however, that computing is typically not a component in these sustainability curricula, perhaps in part, because computer scientists themselves do not actively recognize its relevance to sustainability. Yet computing is pervasive and transformative, potentially
affecting human behavior in disruptive ways, so it seems wise to consider it a core part of in the emerging science of sustainability.

**Computing and Sustainability**

Sustainability science can be reasonably viewed as a new and vitally important discipline, but sustainability concerns should not be stove-piped. If we are designing a planet that sustains humanity for millennia (or even centuries and decades) at anything like current levels, with wealth acceptably distributed, sustainability motivated thought and action must be at the core of everything we do and must permeate the societal milieu. Considering that computing is already embedded in much of society, the prescription that sustainability should be so embedded would result in a frequent and necessary alignment of sustainability and computing. These realizations have only recently started to take center stage.

In May 2008, the Organization for Economic Cooperation and Development (OECD) hosted the International Workshop on Information and Communications Technology (ICT) and Environmental Challenges in Copenhagen, following projections on ICT's growing environmental footprint.\(^{10,11}\) The workshop was convened to share strategies on mitigating these footprints, to include energy, greenhouse gasses (GHG), and waste. These direct or first-order effects of ICT—during the use, manufacture, and disposal phases—are typically detrimental.

Importantly, the speakers and national delegations also discussed ICT's higher-order effects, many of which lead to decreasing ecological footprints in other sectors such as travel and transportation. Examples of computing's second-order effects include more accurate and rapid identification of species' populations through image and audio recording and processing, static and dynamic routing of vehicles to eliminate congestion and the idle time associated with it, the use of video-conferencing systems instead of travel for meetings, and proposed smart grid applications such as electricity load balancing.

In turn, third-order effects of ICT alter the ways that people and other processes operate, in quality and/or quantity, and these third-order effects can have profound effects, both positive and negative, on ecological footprints. For example, rebound effects occur when efficiency improvements in the per unit costs (such as energy) of a process result in the increased use of that process so that the collective costs (notably energy used) becomes even greater than the collective costs before the "improvements." These rebound effects are but one example of unanticipated (though not necessarily unforeseeable) effects that are detrimental to the environment. Conversely, ICT is responsible for improved data collection and evidence-based decision making, which itself might increase these behaviors.\(^{8,12}\) The Oberlin dorm energy monitoring project, for example, used computing technology to visualize energy and water usage in an attempt to alter their human behavior.\(^{13}\)
The OECD 2008 and 2009 meetings resulted in an important conceptual framework for expressing relationships between computing and the environment. Coincident with this, mathematicians and computer scientists were hosting workshops on sustainability themes. The NSF awarded the Computer Science and Telecommunications Board (CSTB) of the US National Academy of Sciences a grant to explore, organize, and report on the opportunities for computer science research contributions to sustainability. More recently, in February 2011, the Computing Community Consortium (CCC) of the Computer Research Association (CRA) convened a similarly intended meeting, issuing a report on the broad swath of challenges at the intersection of computing and sustainability, requiring truly interdisciplinary partnerships between computing researchers and domain scientists.

Taken from and nicely abstracting the CCC report, Figure 1 highlights the critical role that observational data and computational models play in sustainability science. Challenges in the future of modeling include downscaling global models, say of climate, to better inform regional planning and policy as well as the integration of various sources of information, from social and physical, to plan for the human burden on the natural environment. Some of these challenges might be met by agent-based modeling approaches, where “agents”
correspond to small regions and/or particular information sources.

The CCC report makes recommendations for computing subdisciplines, a few of which we can highlight here. For example, social computing is changing the way that humans communicate, collaborate, compete, and play. Yet, we have not substantially tapped into the possibilities of social computing for advancing sustainability agenda. Encouraging new, sustainable behaviors and growing collective intelligence through social networking is a goal, though finding the incentives that will motivate people to act is a challenge. Green IT refers to mitigating the first-order energy and material effects of computing due to its manufacture, use, recycling, and disposal. Advances in energy efficiency and energy harvesting through GHG-neutral means are relevant. Software is also relevant in areas such as server virtualization and all forms of intelligent control.

In addition to research and practice, the report also stressed the importance of education, in particular the infusing of computing curricula with sustainability, and inversely the infusion of computation into sustainability curricula. Finally, we can extrapolate beyond the US context in which the CCC report was prepared and emphasize that government funding provides incentive for the interdisciplinary and international research collaborations necessary to advance sustainability desiderata. These collaborations would not simply be between environmental scientists and computer scientists, but because humans are key to sustainability solutions, there is a great need for “sociotechnical sciences that anticipate, evaluate and design cognizant of rebound effects” and other influences of technology on human behavior.

**AI and Sustainability**

Finally, we come to the area that this article inaugurates: AI and sustainability. The computing areas that I highlighted earlier all invite AI methods to facilitate progress. In green IT, for example, there are intelligent controls during use phases, and planning and scheduling concerns during manufacture, such as shortening supply chains to reduce ecological footprints. There is also a nascent movement toward AI for sustainable design, including cradle-to-cradle design, intended to eliminate waste through low-energy reclamation processes.

Although Figure 1 labeled “intelligent systems” as a distinct area from optimization and cyber-physical systems (CPS), they are not mutually exclusive. Optimization has a rich history both in and outside of traditional AI boundaries. Exemplar applications of optimization for sustainability include supply-chain planning, optimal wind-farm arrangement on small and large scales, and reserve and corridor design, where land is purchased for the benefit of selected species under budget constraints. We can imagine that in each of these examples, climate change (whether the reader believes it is human caused or not) will alter what is optimal, and thus characterizing solution robustness and adapting solutions in the face of change are important challenges.

Machine learning is another important methodology for sustainability. Machine learning methods are used for such varying applications as learning to identify and count individuals, or otherwise estimate distributions of a particular species; learning patterns of use for different appliances from simple household sensors; and learning to predict failures in aging civil infrastructure.
Learning is also integral in realizing a great promise of computing for customization, where nuanced characterizations of individuals are possible that are much richer than binary-valued opinion-poll labels such as “liberal,” “conservative,” “wasteful,” or “thrifty.” With these richer characterizations, we can fit sustainability relevant actions to individuals, resulting in large savings in energy and waste, for example, in comfort-driven services. Consider hotel air conditioners that are left running so that a new guest will not experience a few minutes of uncomfortable warmth. In an integrated cyber-physical-social network that has learned my preferences, air conditioners in a room reserved for me will be shut down, at least until my arrival.

Intelligent CPS, as the last illustration suggests, are yet another class of systems that will receive considerable attention in this new AI and Sustainability department. CPS is at the intersection of computing and the physical world. It includes static and dynamic sensor networks and smart appliances, buildings, cars, highways, and cities. Through monitoring and action in the physical world, CPS will have second-order effects relative to sustainability concerns, and these effects might be environmentally harmful or beneficial. Robotics is another highly relevant CPS class, particularly for monitoring the environment. Considerable work is underway on autonomous underwater vehicles (AUV) for monitoring of ocean and freshwater ecosystems and autonomous aerial and ground vehicles for monitoring in emergencies ranging from nuclear accidents to wildfires.

Looking Ahead
This article has barely touched on the vast possibilities for intelligent systems to address sustainability concerns. Work in this area will often boil down to augmenting human decision-making capabilities in the face of uncertainty and other complexities. In some cases, such as emergency response, intelligent systems will reduce the latency of response while increasing its quality. In other settings requiring and allowing for deliberation, intelligent systems can facilitate better-informed and better-reasoned decisions. We can hope that reliance on intelligent systems will have positive second- and third-order effects on the manner in which humans reason—a machine learning system, for example, typically requires data and decisions stemming from their recommendations will be informed by evidence, perhaps serving as exemplars of reasoning. Pedagogical goals and strategies can be designed into these systems from their inception, thus not simply offloading work and/or providing recommendations, but helping humans to become better problem solvers at the same time.

Clearly, research, education, and application in sustainability will challenge AI along many trajectories, taking us outside our usual boxes, as application inspired and use-driven basic research often does. It’s an important time for AI as we grapple with the complexities of designing a sustainable and equitable society. I am excited to see what emerges and hope that much of it will be reported in these pages.

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References


