POINT OF VIEW

Cyber-Eco Technology: Engineering of Ecological Systems

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The Earth's human population and per capita use of resources have grown dramatically in the past century. Rapid conversion of land from wilderness to agricultural and urban use, air and water pollution, drawdown of potable water resources, overfishing, and increased use of fossil-based fuels have changed the Earth's natural systems, as indicated by increasing average global temperatures, invasions of exotic species, modification of the level and chemistry of our oceans, and rapidly declining biodiversity. These effects are unintended; we have been accidentally engineering the Earth's processes—ecological, hydrological, and meteorological, among others—across all spatial scales.

Increasing awareness that these changes could cause potentially cataclysmic knock-on effects, including extreme weather events, crop failures, disease migration, droughts and flooding, water and food shortages, and die-off of ecosystems that provide critical services to humanity, will inspire us to develop cyber-eco technology and catalyze a new paradigm: deliberate engineering of ecological communities and the ecosystem-level flows of mass and energy that sustain themselves and humanity. Cyber-eco engineering will harness ecological systems' attributes of biological adaptation and evolution, rather than assume that they are static or that their associated processes are beyond our predictive powers. The resulting cyber-eco systems will be robust to climate change and enable us to manage and control man-made and natural systems both directly and via climate-ecosystem feedbacks.

These engineered systems—terrestrial, aquatic, and maritime—will exploit ecological communities' abilities to not only produce food and

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store carbon, but also to capture and store renewable energy, treat waste, clean the air, and manufacture medicine. For example, solar parks with engineered ecosystems will generate and store multiple types of energy and conserve plant communities while providing water resource management, food, and recreation. We will be able to genetically program ecological systems, not by creating new forms of life, but by designing community-level genomes and their expressed phenomes—dynamic assemblages of plants and plant populations. In contrast to many extant geoengineering proposals that target planetary-level processes, cyber-eco engineering has two benefits. First, it harnesses the resilience and diversity of life, rather than single-dimension chemical solutions with difficult-to-predict effects at meaningful scales. This enables technology that in its early stages makes possible the design of ecosystems that adapt to climate change, but through advances becomes a means to control the climate via understood climate-ecosystem feedbacks. Second, it can be scaled up gradually as our knowledge base grows through experiments, enabling early identification and prevention of negative effects.

Genetic engineering as we know it today (in, for example, genetically modified crop plants) is not a requirement. While genetically engineered organisms can be incorporated where needed and where proven safe and approved via open, democratic processes, cyber-eco technology will exploit the rich power of design at higher community and ecosystem levels through selection of existing species and genotypes.

By selecting species and genotypes using engineering principles, we will have the capacity to optimize community phenomes that cope with uncertainties in climate predictions and enable us to generate resources sustainably and manage our climate. But achieving this goal will require a suite of technological innovations. Just as the 20th century's aerospace revolution was woven from innovations in aerodynamics, propulsion, and the electronics for communication and computation that underpin modern guidance, control, and navigation, the 21st century's revolution in cyber-eco engineering will be a tapestry of engineering innovations.

To understand how to network individuals and their genomes, from trees to microbiota, into community genomes and phenomes, innovations from across the engineering disciplines will be required. For example, building on continued progress in understanding the design principles of complex-engineered systems, we will need layered architectures for networked, hierarchical dynamic systems that admit data-driven model inference. Advances in signal processing will enable model and state inference of these complex systems based on massive, heterogeneous data sets. Control theory and design will illuminate control and planning over multiple time scales, where the system inputs are genotypes and populations that make up an ecological community. For example, mixtures of intraspecies genotypes are inputs that can provide robustness to uncertainties in climate predictions. These control algorithms will incorporate models informed by communication and information theory that describe how individual organisms and populations collaboratively compute their way to health via exchanges of information, energy, and mass.

Arrays of terrestrial and aquatic sensor and sensor/actuator networks will be deployed globally over elevational, latitudinal, and urban-to-rural gradients in observational and experimental initiatives, along with analogous networks for maritime studies. These arrays will exploit new microscale and nanoscale bio, chemical, and biochemical sensors operating in gaseous, liquid, and soil media that will integrate electronic, microfluidic, and genetic/genomic technologies. Multispectral high-resolution *in situ* 3-D above- and below-ground imaging will enable unprecedented monitoring of ecosystem activity and health when combined with airborne and satellite imaging. Self-monitoring plants will be engineered to integrate bioelectronic sensors operating at molecular and cellular scales, perhaps with the sensors implemented as mutualist microorganisms or by the plant's own genome. Other plants could be designed as bioelectronic sensors that monitor environmental processes. Data-driven hydrological models will enable water conservation and treatment. Where necessary, ubiquitous sensing of water availability and actuation of irrigation will ensure establishment of new systems.

The roadmap to sustainable cyber-eco systems will arise from interdisciplinary innovations in new disciplines that incorporate knowledge from engineering, ecology, cell and molecular biology, microbiology, genetics, genomics, epigenetics, hydrology and soil sciences, climate science, statistics, and computer science. Three core technologies will be developed. First, we will create a vast genetic/genomic database of organisms and their networks of interaction, along with model reduction techniques to reveal the foundation species that are primary ecosystem drivers. New research communities will also develop networked dynamical system models. We will use ecosystem-level genomic and phenomic signal processing techniques for identification of structure and parameters and develop new, petascale computational tools for inference and prediction. Future generations of climate models that scale from continents to microclimates will enable prediction of climate for planned deployments of cyber-eco systems. These two components—hierarchical catalogs of dynamic ecological networks and high-resolution climate forecasting—will be integrated into system models that map genomes, populations, soil types, and changing climate into dynamic hierarchical ecological phenomes from individual to community to ecosystem levels. These models will then underpin sophisticated computational tools

that enable modeling, analyzing, simulating, and optimizing design of systems that simultaneously supply multiple ecosystem services, e.g., water conservation, food production, power generation, and waste treatment. These tools will embed statistical uncertainty in measurements and models, enabling the planning of systems that are robust and resilient to an envelope of climates around expected trajectories.

This enterprise need not start from scratch. Early lessons can be learned by instrumentation of ongoing and planned ecological restoration efforts, and we can deploy small-scale experimental systems; both will begin to inform the construction of theory and models. Scaling up, we will design a global network of garden arrays that incorporate dense spatial and temporal monitoring and actuation for additive and subtractive control of temperature, rainfall, soil moisture, humidity, and solar radiation. These facilities must be complemented by *in silico* simulations of communities, ecosystem-level flows, and environmental processes that will be based on new hybrids of computational modeling frameworks, including hierarchies of agent-based and collective dynamics models. To aid understanding of scaling laws and emergent behaviors of these complex systems, the gap between simulation and garden arrays will be filled in with growth chamber and greenhouse systems to replicate natural systems and explore extreme cases. Data from experimental systems across scales will be used to calibrate the *in silico* models. Researchers and land managers can then design larger scale systems with increased intensity of system-level genomic manipulation, and begin introduction of engineered ecosystems in areas where existing systems are at risk of imminent collapse. These efforts will establish the cyber-eco foundations of landscape-scale systems that integrate ecological and technological infrastructure.

This vision is unquestionably ambitious, even fantastic. Yet, when the Wright brothers' biplane made its first flight in 1903, it was inconceivable that a highly complex, distributed engineered system—today's air transportation network—would interconnect thousands of cities with over 50 000 flights every day. With today's anthropomorphic pressure on our planetary systems and human population expected to grow 30% by 2100, we must abandon accidental engineering of our planet and invent a new paradigm of stewardship: deliberate engineering of its systems in order to sustain them and humanity. ■