

Tega Brain

**THE ENVIRONMENT
IS NOT A SYSTEM**

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Figure 1: Seagrass in Tasmania, Australia. Credit: Tega Brain.

In late 2017, Microsoft's chief environmental scientist, Lucas Joppa announced AI for Earth, a new initiative to put artificial intelligence in the hands of those who are trying to "monitor, model and manage the earth's natural systems". AI for Earth gives environmental researchers access to Microsoft's cloud platform and AI technologies, and similar to recent initiatives by companies like Google and Planet Labs, it aims to integrate AI into environmental research and management.

It is obvious that Silicon Valley stands to profit handsomely from the uptake of AI in environmental research and management, as it has from the application of these methods in a diverse range of other fields. From urban design to the justice system, decision making processes are being automated by data-driven systems. And in spite of a growing body of criticism on the limitations of these technologies,[1] the tech industry continues to promote them with the mix of solutionism and teleology that imbues Joppa's words. He urges: "for every environmental problem, governments, nonprofits, academia and the technology industry need to ask two questions: 'how can AI help solve this?' and 'how can we facilitate the application of AI?'" (Joppa)

This paper considers some of the limitations and possibilities of computational models in the context of environmental

inquiry, specifically exploring the modes of knowledge production that it mobilizes. As has been argued by authors like Katherine Hayles and Jennifer Gabrys, computation goes beyond just reading and representing the world. As a mode of inquiry it has a powerful world-making capacity, generating new pathways for action and therefore new conditions. "Computing computes." [2] Computational metaphors are also pervasive as framing devices for complex realities, particularly in the context of research on the city, the human brain or human behavior. [3]

Historic computational attempts to model, simulate and make predictions about environmental assemblages, both emerge from and reinforce a systems view on the world. The word *eco-system* itself stands as a reminder that the history of ecology is enmeshed with systems theory and presupposes that species entanglements *are operational or functional*. More surreptitiously, a systematic view of the environment connotes it as bounded, knowable and made up of components operating in chains of cause and effect. This framing strongly invokes possibilities of manipulation and control and implicitly asks: *what should an ecosystem be optimized for?* [4]

This question is particularly relevant at a time of rapid climate change, mass extinction and, conveniently, an unprecedented surplus of computing. As many have pointed out, these conditions make it tempting (and lucrative) to claim that neat technological fixes can address thorny existential problems. [5] This modernist fantasy is well and truly alive for proponents of the smart city, and even more dramatically in proposals for environmental interventions that threaten to commodify earth's climate conditions, such as atmospheric engineering. [6]

What else does a systems view of the environment amplify or edit out? This discussion revisits several historic missteps in

environmental measurement and modeling in order to pull focus on the epistemological assumptions embedded into a systems perspective. It then asks, what are other possibilities for ecological thought? Does AI have any potential to reveal environments in ways that escape the trapping of systems? Critical to my inquiry is the recent work of Anna Tsing and what she calls, “the arts of noticing”. Tsing’s work offers a starting point for thinking outside of both a systems framework and assumptions of progress (17). Her perspective on ecology and the lifeworlds it describes unfolds and emerges through “encounters” (20) which bring together entities, transforming them in indeterminate ways. Might AI operate through modes of environmental encounters or will it simply amplify “an informatics of domination” (Haraway 162)?

The poverty of numbers

A systems view of the environment reinforced by computation, has numerous precedents, including 18th and 19th century attempts at scientific forest management. This early attempt at centralized ecosystem management through numerical modeling foreshadows the contemporary use of these approaches in the context of computation. James C. Scott traces how the introduction of centralized forestry required forests to be made legible in new ways.[7] Trees in forests were measured, quantified and modeled to optimize harvest and replanting for timber yield. Thus the fastest growing species were replanted in felled areas, and trees became viewed as autonomous machines for producing wood. Those species not harvestable for timber – low lying bushes, fungi and plants (Scott 13), as well as traditional ‘unofficial’ use of forests by local communities – were edited out of the system (Hölzl 436). These scientific or fiscal

forests, were managed with the assumption that complex species entanglements were irrelevant and could be treated as external to a system designed to efficiently transform trees into commodities. Yet after a couple of generations of felling and replanting, yields began to drop and the health of managed forests deteriorated (Scott 20). Viewing the forest as a factory oversimplified the reality of the relations and interdependencies of its species.

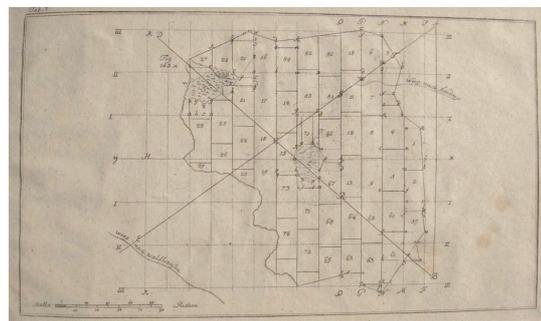


Figure 2: Imaginary forest patch partitioned in 84 sections. Credit: Grünberger, G. (1788) *Lehrbuch für den pfalzbaierischen Förster*, Vol. 1 (München: Strobl), Figure 163 from *Historicizing Sustainability: German Scientific Forestry in the Eighteenth and Nineteenth Centuries* (Hölzl).

The scientific forest failed by its own criteria: timber yield. However it is worth acknowledging that if yield had remained high while biodiversity declined, this history of sustainable environmental management would be remembered as a success, analogous to industrial agriculture. Tsing calls environments that are simplified and optimized to produce commodities “plantations” (435). The economic drivers of capitalism make crop yields the ultimate goal of agricultural landscapes, and shape how they are measured, modeled and manipulated. When a landscape is managed as a factory, its species become assets alienated from their lifeworlds[8] like workers who fulfill HITs on Mechanical Turk with no bearing on each other or what they produce. When the asset

can no longer be extracted, the landscape becomes a ruin and disappears from view, deemed worthless (Tsing 31). Both the plantation and the scientific forest are the results of numerical approaches to landscape management applied in the name of economics. They highlight that data collection and modeling practices are never neutral. Rather, they are contingent on decisions of what is deemed important or trivial in the eyes of the manager and therefore are profoundly driven by culture and economics, class and race.

The fantasy of stability

In the twentieth century, the science of ecology emerged in dialogue with cybernetics and systems theory. There is a rich body of literature critiquing how these conditions influenced environmental research. [9] Cybernetics, first defined in the 19th century by André-Marie Ampère as “the science of governance” was catalyzed as an interdisciplinary field by proponents like Norbert Wiener in the post war decades.[10] It inspired ecologists to pursue questions of control and self regulation in the context of species lifeworlds. Some early ecosystem

diagrams were even realized in the style of circuitry.

Botanist Michael Tansley was among the first to use the term “ecosystem” in 1935 to describe the “systematic” functioning of forests, grasslands and wetlands environments. He saw ecosystems as “the whole system (in the physical sense), including not only the organism-complex, but also the whole complex of physical factors forming what we call the environment of the biome [... these] are the basic units of nature” (299). Like the scientific foresters, Tansley proposed that ecosystems were made of discrete stable units, interacting in ways that tend towards a state of dynamic equilibrium. He also assumed that natural selection favors stability, that “systems that can attain the most stable equilibrium, can survive the longest” (Tansley 299). This idea of ecological equilibrium remains stubbornly influential, as does the idea of the environment as a unified “whole”. As philosophers like Bruno Latour and Timothy Morton discuss, the idea that the “natural world” exists in a balanced harmonious state that is then disrupted by humans reiterates the misconception that humans and environment are separate.[11]

Towards the late 1960s, Tansy’s assumption of ecosystem homeostasis was proving difficult to verify, even in ambitious large-scale ecosystem modeling projects enabled by the availability of computation. One such project was the Grasslands Biome, started in 1968 at Colorado State University. It was an unprecedented attempt to comprehensively model a grasslands ecosystem with a computational model and aimed to uncover new ecological principles (Kwa 1). Employing hundreds of full time researchers, the project involved extraordinary methods of data collection as researchers tried to account for all forms of energy entering and leaving the system, attempting to quantify everything eaten and excreted by

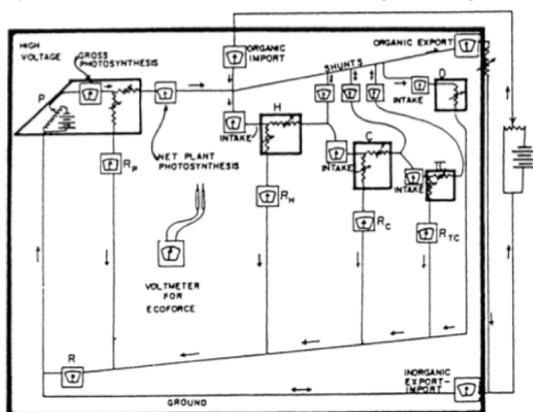


Figure 3: Prominent biologist of the 1960s, Howard Odum’s first presentation of an ecosystem using the symbolism and aesthetic of electric circuit diagrams. Image by Howard Odum, 1960 cited in Madison (218).

all organisms in the biome and then inputting this data into a mathematical model. Students and researchers would follow animals around the grasslands whispering into tape recorders. They would ‘collect’ animals and analyze their stomach content by inserting probes into their digestion systems (Coupland). Soil microbiology was also studied, yet soil invertebrates and highly mobile species such as insects and birds remained frustratingly uncooperative in yielding information to researchers (Coupland 35).

Despite this labor, the Grasslands model, like similar large-scale ecological modeling programs of the time, revealed very few new ecological principles. Deemed “too simplified biologically” despite implementing an unprecedented number of variables (Coupland 154), the model was built with an assumption of default equilibrium. Coupland argues that the Biome Model was simply “a sophisticated version of a cybernetic system [...] and cast [...] the ecologist in the role of systems engineer” (146). The project disproved its foundational hypothesis – that complex ecological realities can be reconciled with mathematical models and be described as abstracted structures of inputs and outputs. “The grandiose ideal of achieving total control over ecosystems, which around 1966 appealed so much to systems ecologists



Figure 4: Processing of replicate biomass samples, ready for drying and weighing, in the field laboratory at the CPER/Pawnee grassland site, Colorado, USA. Credit: Larry Nell, Colorado State University, July 1971.

as well as politicians, was dismissed as a hyperbole” (Coupland 155).

Data collection and modeling practices remain shaped by what is considered typical or atypical, important and peripheral – summations of the boundary conditions of reality. However making these assumptions is difficult. Even with the growing capacity of contemporary computing, it is dangerous to simply assume that more data equals more reality. An example of this is the story of how Joe Farman, a British geophysicist working for the British Antarctic Survey, first observed the destruction of the ozone layer. Farman maintained a single ground based ozone sensor in the Antarctic throughout the 1960s and 1970s, and continued to do so in spite of the launch of NASA atmospheric monitoring satellites that collected vastly larger quantities of data (Vitello). When Farman’s sensor began to show a 40% drop in ozone levels in the early 1980s, he assumed it was damaged and replaced it as NASA’s atmospheric models had reported no such change. After years carefully checking, Farman published this alarming result in *Nature* as the first observation of the destruction of the ozone layer due to human pollutants. Until then, this had been only a theoretical hypothesis.[12] How had NASA’s satellites missed such a marked change in ozone composition? One response from NASA suggests that their data processing software was programmed to discard readings that appeared to be outliers, thus ignoring the drastic changes that were occurring in ozone concentration (Farman). In this case, reality itself was an outlier and assumed to be an error.

The limits of machine learning

What if there was no cap on the amount of data produced from an environment for analysis? Could models be derived from datasets rather than built from theory to avoid erroneous assumptions like those made in the Grasslands model? Could machine learning be adopted to deal with quantities of data beyond human comprehension and prevent any need for discarding outliers? Can these techniques produce a more robust representation of reality, free of human judgement?

These are the arguments made for machine learning. In 1959 Arthur Samuel defined machine learning as “the ability to learn without being explicitly programmed” (McCarthy). Rules are derived from patterns in large data sets, rather than programmed based on theoretical knowledge of underlying structures. “Correlation is enough. We can stop looking for models” proclaimed *Wired* editor Chris Anderson in 2008, in an article titled “End of Theory”. In other words, had the Grasslands model been derived through machine learning, energy flows through the ecosystem could have been estimated based on correlations the data, rather than estimated from inputting data into a theoretical model, hardcoded from hypothesis of ecosystem dynamics. Although this would have prevented erroneous assumptions like default homeostasis, it is important to acknowledge that machine learning substitutes one set of assumptions for another.

Machine learning assumes that enough data can be collected to adequately represent and make predictions about reality. In the context of the environment, this is an enormous challenge given the very limited size of our existing datasets. Another significant

assumption is that the past is indicative of the future. Yet as the sudden unprecedented depletion of atmospheric ozone in the 1980s shows, this to not always be the case. Similarly, climate change means our ability to make accurate predictions from our existing data is diminished. Many environmental datasets like precipitation records span 250 years at best, with the majority spanning a much shorter period.[13] From a geological point of view this is an absurdly small slice of time, and one in which the earth’s climate has been relatively stable. As the patterns, rhythms and cycles in both climatic and biological phenomena are drastically disrupted, it becomes increasingly difficult to make predictions based on this short, stable interval of climate data. William B. Gail calls this the coming of “a new dark age”, where the accumulated observations of Earth’s irreducibly complex conditions are increasingly rendered obsolete. If machine learning approaches are to be adopted, it is important to recognize the limits of these methods.

Dreams of objectivity

Another prominent argument made for the use of AI methods is that data-driven approaches neutralize human decision making by simply representing the world as it is. The proponents of AI for Earth also make these claims to objectivity: “Decisions about what actions to take will be easier to make — and less vulnerable to politicization — if we know what is happening on Earth, when and where. AI can help to provide that information.” (Joppa) However in other realms, AI systems continue to reveal and confirm biases and structural inequalities rather than offering an easy pathway to their neutralization.

For example, defendant risk scoring systems designed to help judges make

decisions to “deliver better outcomes to all who touch the justice system” (Equivalent) have been shown to score black defendants at significantly higher risk for reoffense than white defendants with similar or worse criminal records (Angwin et al.). Systems like these should serve as warnings to other industries implementing automating decisions making, even in the name of environmental management. As theorist Françoise Vergès argues, “adaptation through technology or the development of green capitalism [...] does not thoroughly address the long history and memory of environmental destruction [...], nor the asymmetry of power.” Contemporary environmental challenges directly emerge from violent histories of colonialism, imperialism and the ongoing exploitation of marginalized communities or those living in the global South (Vergès). As such, there is no reason to suggest that AI technologies built and implemented by a cohort of wealthy white men in the US will in any way manage or distribute environmental resources in ways that are equitable for everyone.

Technologies will only ever provide partial fixes if they are not accompanied by shifts in perception and values, along with regulatory change that addresses histories of injustice and “the tradition of belief in progress” (Vergès). More efficient resource use in a system of deregulated capitalism is most likely to beget further resource use rather than net reduction. Microsoft seems to have it backwards in its mission statement “to empower every person and organization on the planet to achieve more”. Wasn’t the idea behind technologies of automation to empower us to achieve less? Or at least prompt a radical rethinking of what ‘more’ is? As Vergès argues, if these logics go unquestioned, mounting environmental challenges will not only continue to accelerate change in an already stressed biosphere, but also further augment environmental injustices.

If the environment is not a system, then what is it?

How else might we think of environments in lieu of the systems metaphor? Tsing offers the concept of assemblage and here I build on her work, understanding environments as open ended assemblages of non-humans, living and nonliving, entangled in ways of life.

Ecologists turned to assemblages to get around the sometimes fixed and bounded connotations of ecological ‘community.’ The question of how the varied species in a species assemblage influence each other — if at all — is never settled: some thwart (or eat) each other; others work together to make life possible; still others just happen to find themselves in the same place. Assemblages are open-ended gatherings. They allow us to ask about communal effects without assuming them. (Tsing 54)

Like Tsing, many authors have taken up the concept of assemblage to round out the simplification and abstraction connoted through use of technological metaphors. Following Latour, to assume a system is also to surreptitiously assume “the hidden presence of an engineer at work”, a presence that suggests intention and that what we can see are parts of a unified whole (*Some Advantages of the Notion of “Critical Zone” for Geopolitics*, 3). Assemblage relieves us of this view, instead suggesting a collection of entities that may or may not exhibit systematic characteristics. The edges of an assemblage are fuzzy – modes of interaction are always shifting and agencies within them are heterogeneous. Katherine Hayles also invokes the term in her inquiry on

cognition in complex human technological entanglements, what she calls “cognitive assemblages” (*Unthought* 3). Hayles chooses assemblage over network arguing that network conveys “a sense of sparse, clean materiality”, whilst assemblage offers “continuity in a fleshy sense, touching, incorporating, repelling, mutating” (118). She continues: “I want to convey the sense of a provisional collection of parts in constant flux as some are added and others lost. The parts are not so tightly bound that transformations are inhibited and not so loosely connected that information cannot flow between parts” (118). Similarly, I take up assemblage as an imperfect descriptor to avoid the hubristic assumptions of a systems view. Stating “I am studying a grasslands assemblage” instead of “I am studying a grasslands system” produces a remarkable shift in expectations and assumptions. This simple substitution dismantles subtle assumptions of fixed categories of knowledge, as well as assumptions that engineering and control are always possible. Instead it foregrounds uncertainty and acknowledges the unknowability of the world.

Rather than describing ecology through interactions or exchanges between entities, Tsing proposes that it emerges through encounters. For Tsing, encounters open new possibilities for thinking. They produce transformation and are therefore indeterminate (63). They are also non-human centered. There can be encounters between different species – say a mushroom and a pine tree – or between lifeforms and non-human materials. Components of a system are implied to be static discrete units, leaving out processes of contamination and transformation. For example when predator-prey relations are described as transfers of energy between components in a system, say a walrus eats a mollusc, it is inferred that the walrus remains unchanged by the encounter. Seeing the

world as made up of individuals sealed off from one another, allows for the assumption of stable categories, and makes the world easier to quantify through data, interpreted as pattern and codified as algorithm. The yield from a data-driven mode of knowledge production is obviously rich and wide reaching, providing new insight into phenomena like climate change. And yet, as the story of Farman’s attention to the atmosphere shows, scaling and automating data collection processes can risk overpresuming the stability of the world and blind us to transformations outside of assumed possibility spaces.

In this way “smartness”, in its current form, produces a kind of myopia. A smart city, home or environment contains networks of sensors automatically pinging data back to servers to train machine learning models of the world. Indeed this is also Joppa’s pitch for AI for Earth: “AI systems can now be trained to classify raw data from sensors on the ground, in the sky or in space, using categories that both humans and computers understand, and at appropriate spatial and temporal resolution.” This statement is worthy of careful consideration. Firstly, how does one decide on an appropriate temporal resolution? In the case of the German forests, it took nearly a century to see that management methods were unsustainable because the life rhythms of a tree are at a vastly slower tempo than those of human economies. Joppa also infers that the world can be revealed by how it appears through “raw sensor data”. Yet this implies the sensors themselves as somehow neutral and overlooks the layers of human decision making that has occurred in their production and installation.[14]

It can also be surprisingly difficult to resolve the world into clearly defined categories. And are these categories stable? Tsing’s argument that encounters produce transformation suggests that neat taxonomies will

never fully accommodate the fluidity and uncertainty of the world. This is particularly apparent in plant systematics where even the definition of species is contested and ever changing (Ernst). In trying to categorize plant specimens, a tension can emerge between how the specimen appears – its phenotype, and how it appears on a genetic level – its genotype. As genetic sequencing techniques have become cheaper and therefore more widely available, plant scientists sometimes find that the species indicated by phenotype does not always match up to the genotype – a discovery that has caused many herbaria to be reorganized. However even when identifying specimen on a purely genetic level, there is still dispute over how species are interpreted.[15]

Data-driven research methods necessitate the collection of huge quantities of data and in doing so, they dismantle opportunities for paying close specific attention to the world. These methods also tend to obscure the many other ways of building understanding. Also, perhaps intentionally, data collection increasingly acts to maintain the status quo. We use data to study problems that would be more effectively addressed through simple political action. The impetus to “study the problem” ad nauseam gives the appearance of addressing an issue while perfectly maintaining the present state of affairs.[16]

Amplifying encounters

How might we reciprocally illuminate the environment and balance our well oiled capacity for imagining it from an all-conquering systems worldview? How might we elevate engagement through the specifics of encounter and narrative?

Ethnography is one possibility. Tsing’s study of the matsutake mushroom explores

what can be learnt from a Japanese mushroom, a lifeform that cannot be cultivated and that thrives in highly disturbed forests. Through her ethnography she shows how close attention inevitably facilitates transformation. Tsing calls this “the arts of noticing”, tactics for thinking without either the abstraction produced by quantification or deeply held assumptions of progress. If we are “agnostic about where we are going, we might look for what has been ignored” (51). As Farman’s ozone research showed, paying close attention rather than outsourcing observation and interpretive capacities can reveal the world in different ways. In particular, attention can emphasize the indeterminacy and messiness of encounters outside of an engineering agenda. It can transform the observer, directly involving us in the weirdness of the world.

Could technologies like machine vision and remote sensing be used to amplify environmental encounters and the arts of noticing our ecological entanglements? The rise of digital naturalism sees the development of apps and initiatives that focus attention on the lifeforms in our various bioregions. Initiatives such as *iNaturalist*, *Merlin Bird ID* and *eBird* invite non-scientists to contribute environmental observations and use either crowd-sourced or “assisted identification” to identify species and build biodiversity databases. Assisted identification utilizes computer vision techniques to guide species identification from images by identifying broad categories and making suggestions. Through this process, the system is also gradually being trained, and over time will therefore make better suggestions. Many scientific institutions also hope that data-driven species identification can help to reduce the bottlenecks in identification processes as human taxonomists are in short supply (Kim).



Figure 5: Deer observations made at the CPER/Pawnee grassland site, Colorado, USA. Credit: Animated GIF made from Adam Curtis' documentary *All Watched over by Machines of Loving Grace*.

It is also worth emphasizing that these apps do not purport to replace human identification but rather facilitate human computer collaboration to reach conclusions quicker. This is significant, as it shows a way that AI can produce more meaningful environmental encounters rather than automate them away. This use case for AI also serves as a reminder that data can be much more than a material for building a simulation or instrumentalizing whatever is being measured. The act of data collection and collaborative identification can amplify encounters and, by extension, yield transformation or what artist Jenny Odell calls “a certain dismantling in the mind.” In observing a local bird, and being assisted to identify it as a magpie, I’m learning and tuning my perception to the lifeworlds I inhabit: I’m subject to transformation.

Accounts of the scientific forest, the Grasslands Biome and Farman’s ozone observations, mostly focus on the success or failure of the science – on whether these projects of observation or modeling succeeded or failed in revealing new patterns, on whether the resultant environmental models proved accurate, and, by extension, on whether they produced new possibilities for environmental management and manipulation. But telling these stories like this, is telling them from a systems point of view. And what tends to get overlooked is how these are

actually stories of environmental encounter though data collection. As encounters, they are also stories of transformation of both the environments and the humans involved. How did the meticulous observation of the environmental assemblages in question shift and transform the people studying them? In itself, this question rejects a false binary between human and environment. It acknowledges the instability of the observer and the tendencies of Western science to edit out intuition, emotion and philosophical recalibrations. The reciprocal transformation that occurs with attention and encounter, what Nobel prize winning geneticist Barbara McClintock called “getting a feeling for the organism”, is not only critical for formulating original scientific hypothesis, but more deeply, for questioning foundational assumptions of what is counted as knowledge and what we then expect knowledge to do.[17] Looking back on the early scientific forests and even on the more recent Grasslands Biome, it is difficult to speculate on how these projects changed the people involved. However, their stories remind us of the irreducibility of an unruly and complex environment. That as hard as we try to contain the world in neat technological metaphors, it will always leak out and transform us.

Notes

[1] See recent books *Weapons of Math Destruction* by Cathy O’Neil, *Automating Inequality* by Virginia Eubanks, *Code and Clay, Data and Dirt: Five Thousand Years of Urban Media* by Shannon Mattern, and the *Machine Bias* Series published by Propublica and written by Julia Angwin et al.

[2] See Katherine Hayles (*My Mother Was a Computer*, 7-31) and Jennifer Gabrys' discussion in *Program Earth* (11).

[3] Sociologist Shannon Mattern warns of the "the city as computer model" arguing that it often hinders "the development of healthy, just, and resilient cities" (*The City is Not a Computer*). Psychologist Robert Epstein highlights similar issues in the context of brain research observing that historically, metaphors for cognition have always been drawn from the dominant technology of the time – hydraulics, springs and mechanics, electrical circuits and now computation. Epstein argues that the ubiquity of information processing metaphors in brain research may well be constraining the field by confining hypotheses and explanations to those that align with computational processes. These metaphors equally constrain approaches to environment inquiry.

[4] This question is inspired by Shannon Mattern's discussion of the city as a computer metaphor (*The City is Not a Computer*).

[5] See Bratton et al. (9); Gabrys (230); Stengers (1000), and Szerszynski et al (2818).

[6] See Temple on the planned atmospheric tests scheduled to occur in the US in 2018.

[7] See James C. Scott's well known account of scientific forestry in *Seeing Like a State*.

[8] I use the word 'lifeworlds' following Anna Tsing who describes objects in capitalist exchange as being alienated and "torn from their lifeworlds" (121).

[9] Many authors discuss the influence of systems theory on ecology, such as Elichirigoity, *Planet Management*, and Latour, *Some Advantages of the Notion of "Critical Zone" for Geopolitics*. Some also consider the influence of cybernetics such as Haraway, *The High Cost of Information*, and Jennifer Gabrys, *Program Earth*.

[10] See Wiener's landmark 1948 book, *Cybernetics*.

[11] Latour's concept of "naturecultures" introduced in the *Politics of Nature* is an attempt to collapse a false binary between the human concerns and nature. Morton, builds on this in *The Ecological Thought* that also rejects this bifurcation.

[12] The theory of ozone destruction was published by Molina et al.

[13] See Simpson.

[14] See Gabrys; Bratton et al.

[15] See Fazekas for discussion of differences in species definitions. Hull discusses how these uncertainties have led to the concept of reciprocal illumination in plant systematics. This concept acknowledges the multiple methods for classifying and naming species.

[16] Now discontinued, *The Human Project* was an example of data collection in lieu of political action. The project planned to address issues of health, urban design and inequality by collecting huge volumes of data from 10000 New Yorkers over 20 years.

[17] See Keller's biography of McClintock's life.

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