The Ecology of Arcadia

This is the way we dream of Eden. We cannot help feeling that it still exists, but just beyond our reach--beyond the wall of dark fire kept roaring by the cherubim of the brain.

- Evan Eisenberg, *The Ecology of Eden*

Bodies in Paradise

The Arcadian Shepherds, Poussin, 1638.

In Nicolas Poussin's 1638 painting *The Arcadian Shepherds*, or *Et in Arcadia Ego*, unsettled shepherds gather around a starkly cut stone tomb, while one of them traces with his finger the inscription; "and [yet] in Arcadia, [here too] I am." They are accompanied by an imposing female figure, stylistically based on the Juno Cesi statue currently in the Capitoline Museum. With her diadem, blue and yellow clothing, and hand on the back of the shepherd pointing at the letter R on the inscription, she most likely represents the personification of Reason, offering some form of comfort or interpretation of their disruptive discovery. A laurel tree rises behind the tomb, and the shepherds are wearing laurel wreaths. The line is adapted from Virgil's 5th Eclogue, where two shepherds lament the death of Daphnis, son of Hermes, lover of Pan, and follower of Artemis, joined in mourning by the whole of the natural world;

spargite humum foliis, inducite fontibus umbras,
pastores (mandat fieri sibi talia Daphnis),
et tumulum facite et tumulo superaddite carmen:
'Daphnis ego in silvis, hinc usque ad sidera notus,
formosi pecoris custos, formosior ipse

Sprinkle leaves upon the earth
wrap the springs in shade,
shepherds, such toll does Daphnis ask
and build a tomb, and upon the tomb write this verse:
I am Daphnis of the forest, known from here to the stars
guardian of fair flocks, fairer yet himself

Daphnis, from δάφνη, *daphne*, bay laurel, was a mythic pastoral culture hero. Exposed as an infant in a laurel grove, and raised by Sicilian shepherds on the slopes of Mt. Etna, he was said to have sung the first pastoral poems. He lived in prototypical pastoral fashion; tending herds, composing songs, dancing with Pan and Artemis. His death was brought about after he fell in love with Aphrodite herself (implicit in Theocritus' telling), wasting away with the withering vegetation in the heat of summer, and entrusting his pipes to Pan as he was hauled off to Hades by Eros, the general fate of any mortal lover of the goddess.

While Daphnis was Sicilian, the essential concept of the lost pastoral idyll that he represented became associated with the province of Arcadia, in the central Peloponnese, hence the location of his tomb. Arcadia is named after Arcas, its first mythological king, the son of Zeus and Callisto. His mother was a nymph and lover of Artemis, seduced by Zeus disguised as the goddess, and later transformed into a bear by an enraged Hera, after birthing Arcas hidden from Hera's wrath in the woodlands that would later bear his name.

Poussin's painting is the most well known of several Renaissance artworks depicting an Arcadian tomb featuring this inscription, in which, as well as Daphnis, the *ego* referenced is variously interpreted as death itself, or 'the dead' in aggregate. I will describe these as the admonitory and nostalgic interpretations respectively.

Et in Arcadia Ego, Guercino, 1618

The modified line from Virgil was coined by Cardinal Giulio Rospigliosi in 1618, who commissioned Giovanni Francesco Barbieri (better known as Guercino) to create the first painting on this theme. In Guercino’s admonitory interpretation, a skull placed atop the tomb clearly drives the *memento mori* point home, and there is no regal matronly figure to reassure the shocked shepherds.

By the time Goethe adopted *et in Arcadia ego* as the motto for his Italian Journey (1816), after seeing Guercino’s painting, the nostalgic interpretation had generally taken hold, with the *ego* being the occupant of the tomb looking back upon the pleasures of life now lost to them. In Schiller’s German translation, "Auch ich war in Arkadien geboren" (I, too, was born in Arcadia), this interpretation reaches its fullest extent, with Arcadia becoming the naming concept of a state of lost harmony experienced by the living also; a pastoral second Eden, with enough inhabitants to essentialize the forms of human society, and enough realism to at least seem plausible as a lost age, while also accounting for our sense of loss in aging, sickness and death.

Many of the specific features of the Arcadian ideal; rolling hills, misty sun dappled valleys, scattered groves of oak and poplar trees, derive from actual landscapes common in the geographical Arcadia. As a landlocked and mountainous interior region unsuitable for large scale crop agriculture, much of it was indeed sparsely inhabited by pastoralists, said by classical urbanites to have their own distinctive mythology, and to preserve ways of life long lost in teeming cities like Athens and Alexandria.

Arcadian Ecology

Arcadia, Central Peloponnese, Greece

Gilbert White’s tombstone, Selborne, Hampshire

a pilgrimage to [White’s] tomb in his native village of Selborne has become almost a necessary act of devotion on the part of every lover of nature.

- Edward Blyth, intro. to *The Natural History of Selborne, With Its Antiquities, Naturalist’s Calendar, &c* (London: Orr & Smith, 1836)

However universalized its messaging, the literary and artistic concept of Arcadia remained centered in Ancient Greek tropes until the late 18th century, when a version of it was incorporated into the foundations of ecological science. Parson-naturalist Gilbert White's *The Natural History and Antiquities of Selborne* was published by his brother Benjamin in 1789, giving a beatific vision of the ecology of the English countryside on the verge of industrialization, and providing the framework for further development of the Arcadian ideal. His intricately detailed observations served to situate Arcadian concepts within a 'timeless' world of pre-industrial, pastoral harmony, mapped by the flight paths of swallows:

> All the summer long is the swallow a most instructive pattern of unwearied industry and affection; for, from morning to night, while there is a family to be supported, she spends the whole day in skimming close to the ground, and exerting the most sudden turns and quick evolutions. Avenues, and long walks under hedges, and pasture-fields, and mown meadows where cattle graze, are her delight, especially if there are trees interspersed; because in such spots insects most abound. When a fly is taken a smart snap from her bill is heard, resembling the noise at the shutting of a watch case; but the motion of the mandibles are too quick for the eye.
>
> — Gilbert White
> In Letter to Daines Barrington (29 Jan 1774), in *In The Natural History and Antiquities of Selborne* (1789), 169-170.

Note the seamless integration of the features of the cultivated landscape with natural processes, as though the mown meadows are as much a part of an *a priori* system as the trees. Over the centuries that the book has remained in print, the image of Selborne has come to serve as an icon of all that was lost with industrialization, with White's simple G. W. inscribed gravestone continuing to receive regular visitors. "Spatially sequestered, Selborne has evaded the modernizing passage of time, not only in the present but always. Reading and visiting permit a return to a sense of place as permanence that has otherwise been lost. . . .The pastoral ideology came to instantiate not only the familiar geographical contrast between a virtuous countryside and corrupt city, but also a temporal contrast between a settled, idealized past and a present marked by development, social instability, and alienation" (Traveling in Place: Gilbert White's Cosmopolitan Parochialism, Tobias Menely, 2004).

But even in Selborne, change was possible. White was among the first to suggest that swallows were annual migrants, rather than overwintering in hidden hibernacula. His focus on events in the atmosphere also led to his detailed description of the effects of an ash cloud which spread across Europe from the summer 1783 Laki eruption in Iceland. There is palpable dread in White's account of Selborne subject to external influence: "[The] peculiar haze, or smokey fog, that prevailed for many weeks in this island, and in every part of Europe, and even beyond its limits, was a most extraordinary appearance, unlike anything known within the memory of man. . .The sun, at noon, looked as blank as a clouded moon, and shed a rust-coloured ferruginous light on the ground, and floors of rooms; but was particularly lurid and blood-coloured at rising and setting." Concluding that "[there] was reason for the most enlightened person to be apprehensive," White alludes to "Milton's noble simile of the sun, in his first book of *Paradise Lost,*" adding an apocalyptic note to the chaotic shock of climatic instability:

. . . As when the sun new-risen
Looks through the horizontal misty air
Shorn of his beams, or, from behind the moon,
In dim eclipse disastrous twilight sheds
On half the nations, and with fear of change
Perplexes monarchs: darkened so yet shone
Above them all the Archangel . . .

- Milton, *Paradise Lost*, Book 1, 594-600.

Luciferian change could also come from the human world. The following year, he witnessed one of the first hot air balloon journeys, seeing "a dark blue speck at a most prodigious height dropping as it were out of the sky, and hanging amidst the regions of the air,. . .The machine looked mostly of a dark blue colour, but some times reflected the rays of the sun. With a telescope I could discern the boat and the ropes that supported it. . .I was wonderfully struck with the phenomenon, and, like Milton's "Belated Peasant," felt my heart rebound with joy and fear at the same time. . . . At last seeing how securely they moved, I considered them as a group of cranes or storks intent on the business of emigration." The flight of the balloon had been heralded by plumes of smoke rising from newly industrializing London.

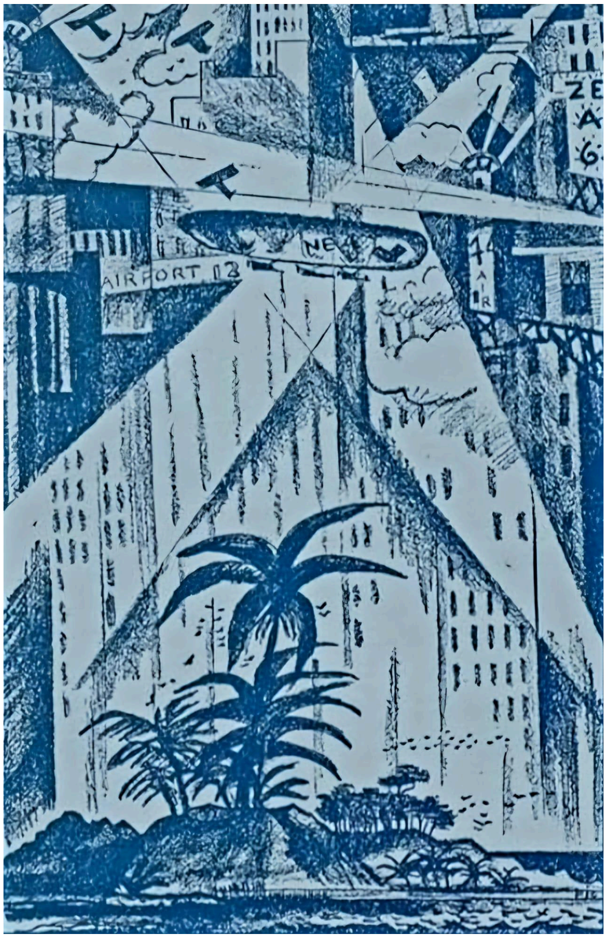
Selborne has been in print continuously since publication, and with its tracing of the networks of energy transfer between organisms, and cumulative approach to the gathering of natural knowledge, is a foundational text of modern ecology. White wrote just as the concept of 'species' in the current sense was originating; the influential 10th edition of Linnaeus' *Systema Naturae* came out in 1758. Darwin was heavily informed by White's observational style, which he projected back into a concept of deep time derived from his reading of Charles Lyell's *Principles of Geology* (1833), adding directional change to White's steady-state ecological universe.

Albrecht Dürer, *The Great Piece of Turf*, 1503.

Darwin's image of the tangled bank on the final page of the *Origin of Species* at first glance resembles White's description of swallows, or Durer's photorealist treatment of common field weeds: "It is interesting to contemplate an entangled bank, clothed with many plants of many kinds, with birds singing on the bushes, with various insects flitting about, and with worms crawling through the damp earth." But reading on, we find that "these elaborately constructed forms, so different from each other, and dependent on each other in so complex a manner, have all been produced by laws acting around us. . .Thus, from the war of nature, from famine and death, the most exalted object which we are capable of conceiving, namely, the production of the higher animals, directly follows" (Darwin, *Origin of Species* (1869), 429).

Enraptured by the vertiginous scope of the trace of life through deep time, Darwin sings his new metaphysic; "There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved." This introduction of systemic flow to the Arcadian vision represents the law of natural selection with modification as a new force in the world, defining the properties of living systems as fluid, with thermodynamically unusual patterns of temporal evolution. In the words of systems ecologist Alfred Lotka, "[the] principle of natural selection reveals itself as capable of yielding information which the first and second laws of thermodynamics are not competent to furnish" (Lotka, *Contribution to the Energetics of Evolution*, 1922).

Imperial Ecology



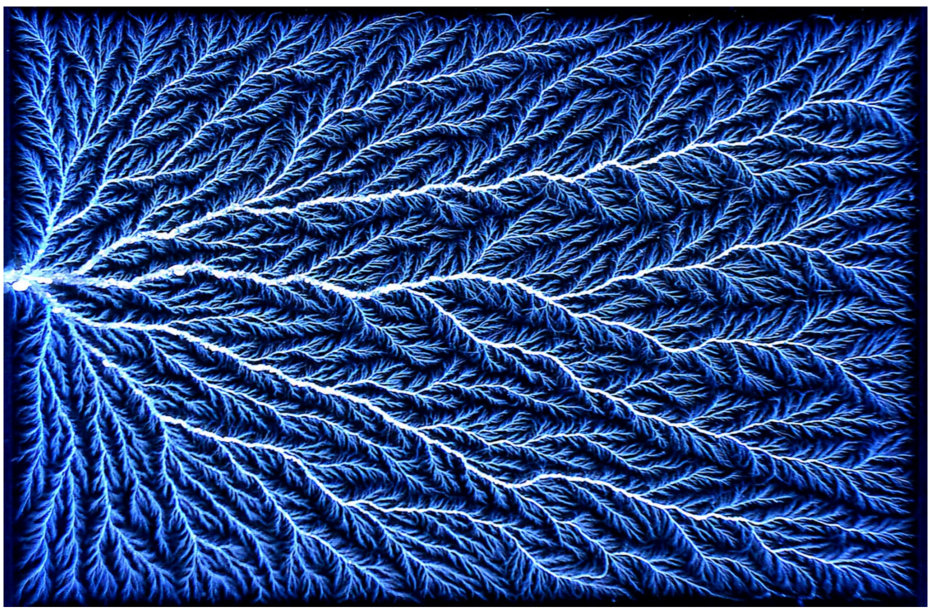
Peder Anker, *Imperial Ecology* (2002), Cover Image

Donald Worster, in his 1977 book *Nature's Economy: A History of Ecological Ideas*, contrasts White's Arcadian ecology with a tradition he calls "imperial ecology," descending from the ideas of Francis Bacon, focused on resource extraction and intensive human management, and intimately connected with European colonial expansion. Worster represents this tension as a fundamental dialectic in 19th and early 20th century ecological thought. In the brave new world of the imperial ecologists, "[all] the Selbornes of the world, it was commonly predicted in expansive rhetoric, were to be torn down and their equilibrium between man and nature replaced by a more aggressively artificial, humanized landscape: a new world in which science would give mankind absolute power over the land and its creatures" (Worster, 1977).

As the Christian understanding transformed the problem of Arcadia from a lost harmony between gods and humans, to the persistent presence of death in any earthly paradise, so the emissaries of empire counterposed industrial progress and colonial management to an Arcadia now containing the doomed pre-industrial world. Ecological networks began to be represented as living systems in danger of death or the draining of their vital energy by the ever increasing needs of the expansive cities and factories. While ecosystems were seen as a source of raw materials, there was not a recognition at this point of externalized costs or ecosystem services. The choice was between two worlds, framed in terms of temporal progress.

The image of the preindustrial ecology of Selborne became the ideal of a natural, harmonious ecosystem, in danger of passing beneath the wheel of human industry. For Darwin, Selborne was a flash frame of ecological functioning, a time slice through which to back project the evolutionary process. But even White, unsettled by ash clouds, balloons and smoke, knew that this "equilibrium between man and nature" was tenuous, and as we know, there are bodies in Arcadia. To illuminate them, we must explore the properties of living systems.

Living Systems



Litchenberg Figure, or captured lightning. Credit, Stoneridge Engineering

There are many ways that a physical system can exhibit stability and growth over time. For the purpose of defining some properties of living systems I will here term two forms of stability 'crystalline' and 'cybernetic'. A crystalline system is closely defined in its initial construction, and exhibits order in the regularity of its parts and of additions to them, for example the regular growth of a crystal. But this order is only laid down during formation, and will inevitably be slowly lost through progressive structural degradation over time. Crystal growth occurs due to extrinsic physical factors, and we do not speak of crystals seeking to maintain favorable conditions for growth.

A cybernetic system (from κυβέρνησις, steering), contains self-stabilizing components that update over time in response to sensed external or internal conditions; for example, a ship's autopilot, or a thermostat. Systems that sense and regulate their internal states are called homeostatic; they respond to deviations in internal conditions by causing a countervailing change in response, restoring stability. Cybernetic responsiveness to external conditions, homeostasis, and self-replicative ability are the most basic properties of living systems.

When these properties are projected through the deep history of the Earth biosphere, they result in the distinctive pattern of the evolutionary process, in which living systems seem to generate ever-increasing order in contradiction to thermodynamic law. This contradiction is avoided when a living system is seen in energetic context. All living systems are also energetically open systems; they self organize to maximally detain and utilize energetic flux passing through them to build internal structure. This property, that "[for] a finite-size flow system to persist in time (to live) it must evolve such that it provides greater and greater access to the currents that flow through it (Bejan, 1996), has been termed the constructal law.

A forest, a coral reef, a multicellular organism, a biofilm, a bacterium; these are all living systems, at a vast range of spatiotemporal scales, organized according to the biospheric constructal law of the principle of natural selection, which can be considered "a *fourth law of thermodynamics*, [specific to living systems] since it is the controlling principle in rate of heat generation and efficiency settings in irreversible biological processes" (Odum, *Ecology*, 1963).

What then, in this analysis of living systems, is Arcadia?

The Pastoral Edge

Λέλειπται δή, καθάπερ ἐν ταῖς σμικραῖς νήσοις, πρὸς τὰ τότε τὰ νῦν οἷον νοσήσαντος σώματος ὀστᾶ, περιερρυηκυίας τῆς γῆς ὅση πίειρα καὶ μαλακή, τοῦ λεπτοῦ σώματος τῆς χώρας μόνου λειφθέντος.

And, just as happens in small islands, what now remains compared with what then existed is like the skeleton of a sick man, all the fat and soft earth having wasted away, and only the bare framework of the land being left.

- Plato, *Critias*, 111b

The concept of the preindustrial world and human lifeways as static, exemplary, and lamentably lost far predates the injection of this nostalgic perspective into the foundations of ecological science. Before there was Arcadia, there was Eden, and any number of myths of lost harmony and the origin of alienation. Human cultural traditions universally produce these stories. But Arcadia contains cadavers rather than world trees. What common thread of loss and apprehension unites the shepherds discovering Daphnis' tomb with White's invocation of the Satanic light of an ash-obscured sun?

Arcadia the concept is not a place, but an edge; it “contains in its ripeness the germ of its own spoiling” (Eisenberg). The image of a pastoral landscape as homeostatic is only possible due to a severe lack of temporal perspective. As White was describing the flight of the swallow over the mown meadow, the most rapid change in energy flux in the history of the biosphere was gathering pace. Rather than a timeless refuge, pastoral systems are one of the first results of this transformation. Historically, they were its leading edge.

The foundational image of ancient Arcadia was “the hills in which herdsmen summer their flocks--in the classical world, the border between tilled land and wilderness.” These borderlands could be located along the expansion front of an agrarian society, or form pockets “left behind” for reasons of climate or topography. Eisenberg goes on to note that “[this] setting is especially apt in that pastoralism is in the short run the easiest and pleasantest, in the long run the most destructive of ancient ways of life.”

Ancient Arcadia itself was not spared from widespread erosion and deforestation due to relentless goat browsing pressure, which has some responsibility also for maintaining the parkland-like landscape associated with the concept. The currently somewhat improved ecological state of the region is due to ongoing state-imposed goat population reduction. This started with the Metaxas regime's 1937 declaration of “war against the goat,” featuring compulsory slaughter of goats that entered designated forest areas, and forcing shepherds to move to cities or switch to field agriculture.

Ancient authors were well aware of the damage caused by overgrazing, and of the instability of pastoral systems. Throughout classical discourse a dialectic developed between the positions that the observed deterioration of Mediterranean ecology under human exploitation was an inherent result of the general aging of the earth, as posited most notably by Seneca, or that it was caused by human mismanagement and excess. Pliny laments that “[we] blame the barrenness of the earth on its age, as if it were growing old and exhausted. But it is our own faults—our excessive greed for pasture, the trampling of flocks, and the constant burden of agriculture—that have drained the earth of its strength" (*Natural History*, Book 18, Chapter 1).

The corollary that deterioration caused by human mismanagement should be modifiable by improved management was generally not drawn at societal scale. Classical agricultural manuals certainly give descriptions of practices which would preserve soil structure and fertility, but these are couched in terms of individual ethics, to be followed by the virtuous farmer, and address crop agriculture more than pastoralism. By the late 4th century, classical society was suffering from structural problems of sufficient severity to render the question of an organized response moot, and Ambrose rails that "The flocks consume all in their path, leaving the earth as if it were plundered. How will the earth yield her fruits when she is stripped bare by the appetite of beasts and the folly of men?" (*Hexaemeron*, Book 3, Chapter 16).

Given that disharmony and destruction was apparent, and that ancient Mediterranean society did not generally see itself as capable of competent ecological management, because it could not conceive of itself as a system able to offer such a coordinated homeostatic response, there had to be a reason for this obvious relational rupture. Something had to have died. And here we find the body of Daphnis of the forest, the representation of this loss and alienation, who could feed his “fair flocks” in harmony with Pan and Artemis. It is no accident that Daphnis was tricked by Aphrodite into falling for a city-dwelling princess as part of the arc toward his demise. But, as his inscription implies in its switch to direct address in the penultimate line, perhaps Daphnis is alive, and can be found from the forest to the stars, if only we can see past his tomb.

Dark Earth

Anthropogenic Dark Earth, or terra preta, in the archaeological site of Hatahara on the middle Amazon, near Manaus, Brazil (Photo by Manuel Arroyo-Kalin)

“Although you allude to the distinction between terra preta and terra mulata, it may be worth noting that terra preta, which is the most desirable for agriculture at present, is unlikely to have been cultivated indigenously because habitation sites are also burial grounds.”

- Betty Meggers, (letter from Meggers to Woods, May 17, 1998)

This statement by Betty Meggers, one of the leading US archaeologists studying Amazonia in the mid 20th century, belies a set of erroneous assumptions deriving from her cultural context. Exploring her error, and its causes, will illuminate a world where the relationship between human societies and the living systems providing their energetic support developed differently, a world without Arcadian tombs.

There is no intrinsically correct form of the concepts a society uses to structure its relationship between matters seen as internal to its processes, and those seen as forming the external frame of the world within which it is contextualized. Concepts such as Daphnis dead in Arcadia, or the formation and separation of ideas of the “human” and “natural” worlds, come about to explain observed patterns, events, and causes. Given that the entirety of any human societal processes are as fully dependent energetically on plant photosynthetic production as all other parts of the heterotrophic biosphere, accounts of separate and uncontrollable natural forces, and of changes in the complexity of the internal processes and productions of a human society, are part of the formation of a societal self concept, rather than accurate descriptions of energy and influence. Much can be learned by examining which elements of the world a society decides to define as outside of its domain of responsibility, and the ways that this patterns its engagement with reality.

Meggers wrote within an intellectual tradition that was incapable of understanding the evidence before its eyes of large-scale human engagement with the biosphere outside of the familiar frames of field agriculture, pastoralism, and urbanism. In Amazonia, humans created and lived within a managed forest over thousands of years and miles, in a manner invisible to Euro-American lenses. Additionally, Meggers was predominantly responsible for the propagation of the standard view of Western anthropologists and archeologists in the mid 20th Century, that indigenous Amazonians were, at best, agriculturalists of opportunity, scraping a meager harvest from nutrient-depleted tropical soils, famous for their lack of fertility. Her 1971 book *Amazonia: Man and Culture in a Counterfeit Paradise*, introduces the trope that seemingly paradisical Amazonia was a place where nature imposed harsh and intrinsic limits on human habitation.

This view became untenable with the demonstration in the last decades that legends of lost garden cities of Amazonia were in large part historically accurate. This was a result of many avenues of evidence, most compellingly in the last few years with the large-scale use of lidar to uncover remnant structures beneath the forest canopy. A 2022 study in Southwestern Amazonia found that “large settlement sites are surrounded by ranked concentric polygonal banks and represent central nodes that are connected to lower-ranked sites by straight, raised causeways that stretch over several kilometres. Massive water-management infrastructure, composed of canals and reservoirs, complete the settlement system in an anthropogenically modified landscape” (Prümers et al., 2022). https://www.nature.com/articles/s41586-022-04780-4

Amazonia was the domestication site for many of our currently dominant cultivated plants, including cacao, peppers, pineapple, sweet potato and tobacco. Out of the roughly 16,000 known Amazonian tree species, half of the total forest cover is composed of only 227 species, 1.4% of the total diversity, and these species are overwhelmingly those useful to humans, or species that modify their local ecology in a direction favorable to humans. The scale of human management suggests a pre-Hispanic population of around 10 million. Previous estimates under the Meggers hypothesis ranging as low as 500,000 are now discredited. But the fundamental issue remains, that freshly cleared rainforest soil is extremely infertile. In a high energy, high diversity system such as a tropical forest, the vast majority of available nutrients spend almost all their time rapidly exchanging between the bodies of living organisms, which are specialized to quickly absorb decomposition products, leaving little to accumulate as a soil reservoir. So how were all these people fed?

In much of Amazonia, the lower populations in recent centuries allowed a form of shifting cultivation that is often termed “slash and burn”, or swidden agriculture. A plot is cleared of forest, and the felled vegetation is burned on the site, forming a surface layer of soil enriched with nutrients in which crops can be grown for a few years before fertility declines, after which humans move on to a new plot, allowing the first to recover through natural regenerative succession. Assuming no banking of nutrients, this method does impose limits on population density, according to the recovery time, and is only sustainable at low density.

In the Brazilian Amazon, freshly cleared forest soil in an area without history of human cultivation is known as *terra comum*, common soil. Repeated cycles of swidden agriculture result in an accumulation of carbon and other combustion products in the soil, somewhat improving its fertility, this soil is then known as *terra mulata*, brown earth. The most fertile soil, *terra preta*, is enriched in carbon to a greater degree than *terra mulata*, also containing a mixture of compost products, animal bones and feces, pottery shards, and other evidence of human modification. This is the soil that Meggers mistook as residue from burial grounds and middens. But these soils cover between 3 and 10% of the total forest area, far more than could be accounted for through funerary practices, or as the unintentional remnant of a low density population. In Bolivia, the majority of the forested area surrounding watercourses in the llanos could likely be anthropogenic, as nearly all of it is underlain by highly human modified *terra preta*.

Carbon as a soil additive has several unique properties; most importantly, it “adsords” or adheres charged particles onto its charged surface, and is porous with a vast surface area when the feedstocks producing it are burned in the right way. These advantages accrue to the current use of biochar in soil, in addition to it being a fixed and extremely stable form of carbon, with negligible atmospheric return.

Amazonia then is an example of a highly human-modified system, in no sense an untouched wilderness or counterfeit paradise. This was invisible to Western archeologists because the boundaries they expected to see were not present, and the cultivated species were intermixed with the wild ones. Eduardo Neves, Brazilian archeologist at the forefront of the reevaluation of the history of Amazonia, notes that “[the] Indigenous worldview does not differentiate between the domain of culture and the domain of nature. The diversity of the Amazon, the presence of many large nut trees and fruit-bearing palm trees, is a result of Indigenous practices.”

These indigenous practices also increased the carbon held in the land as charcoal many times over what it would have been in the absence of human management. What appeared as wilderness is in reality a garden forest shaped to human design, and certainly not an Arcadian edge. Deforestation for monocultures of soy or cattle pasture is destroying an interwoven artifact of human action as part of the biosphere, not a pristine system alienated from human influence, and replacing it with a simpler, energetically less favorable one.

Once we have the ability to see the relational system connecting the structure of the forest system to the human activities that modified it, conceiving of a system such as Amazonia as in some way separate from its human inhabitants becomes self-evidently erroneous. We have here a cultural blindness and essentialization leading to a lack of recognition of the evidence before our eyes of long-term intentional human management. Similarly, our appraisal of phenomena such as anthropogenic climate destabilization is bounded by the extent of our contextual knowledge, being that the Earth system as a whole is also not energetically separable from its human inhabitants.

From Carboniferous to Carbocene

Carboniferous coal seams

In late 2019, I wrote the article *Deep Time Perspectives on Climate Change*, which was published in Palladium Magazine, where I argued that most of the then-current discourse surrounding climate change was self-defeating in terms of being able to appraise the problem in a way that would admit solutions, that to treat the issue in a manner commensurate with its pivotal importance in the history of the biosphere would require that we leverage force multipliers to meaningfully shift global carbon flux downward, and that the class of methods often termed geoengineering were the ones with most potential to do this.

In the article I argued that an Edenic interpretation of the preindustrial climate, coupled with a lack of understanding of what humans were actually doing, on an energetic level, with our recent rerouting of the carbon cycle, had led to the positioning of climate change among a general class of “environmental” problems, and a lack of recognition of the epochal significance of a single species’ wholesale liberation of energy stored for a significant fraction of the history of the Earth in such a short time period as 200 years. I also argued that this act by our species also confers on us the responsibility to manage global carbon flux in general for the foreseeable future, and that this represents a movement toward homeostatic metabolism for the biosphere as a whole.

In the intervening 5 years, I co-founded the Public Benefit Corporation Living Carbon, and worked with many others to produce an example of the general class of approach that I felt necessary. This was the creation through genetic engineering of trees that assimilated carbon more rapidly from the atmosphere, and were slower to return stored carbon from their dead tissues. We were successful in our technological objectives, introducing a photorespiration bypass pathway into hybrid poplar trees and loblolly pine, which resulted in a 30-50% increase in carbon assimilation rate. We enabled copper deposition in the main stems of trees through introduction of a genetic construct including a metal transporter from creosote bush, in the process sequencing a first draft genome of that species, and demonstrated that similar concentrations in prepared wood blocks halved their decomposition mass loss and carbon return rate.

We were also successful in establishing an infrastructure for rapid propagation of these photosynthesis-enhanced and decomposition resistant trees, and for their integration into mixed stand forests as examples of an aspen ecotype. We demonstrated that the carbon sequestration rate of land planted with these trees could be further improved through ancient management techniques such as coppicing and the production of biochar and other forms of long term carbon sequestration from biomass.

Through all of this, we were mindful of what we were instantiating, from an evolutionary perspective. The photorespiration bypass pathway has a similar carbon assimilation enhancement effect to the metabolic pathway called C4 used by many species of grasses, which had transformative effects on the global ecology after its evolution some 30 million years ago. Trees through secondary growth store carbon far more effectively than grasses, but had not thus far evolved an equivalently efficient form of photosynthesis. Decomposition resistance through metal accumulation was a method to mimic the effect of the Carboniferous drawdown caused by the initial evolution of the wood strengthening polymer lignin, which represented permanent carbon storage until fungi developed the ability to digest it with peroxidase enzymes, in the process ending the most recent period of bipolar glaciation before our current ice age.

I left Living Carbon when the organization reconstituted itself following the recognition that carbon removals achieved by our central project as outlined above would not achieve institutional acceptance in the existing forest carbon markets. Due to its constitution as a venture capital backed startup, dependent on a rapid growth and fundraising cycle, Living

Carbon was forced to take a somewhat more conservative approach to forest carbon removal, efficiently reforesting human-degraded land with diverse tree species with a slower and more incremental involvement of biotechnology. By this point we had created living examples of both photosynthesis enhancement and decomposition resistance, with one of which, photosynthesis-enhanced hybrid poplar, being planted as part of an ongoing streambank restoration and soil remediation effort along the Los Angeles river, where environmental DNA data is also being collected to document changes in ecological functional connectivity over time.

I am continuing to work with these trees, answering basic research questions about their behavior and carbon removal rate in various contexts, as one branch of the nonprofit organization Carbocene Industries (www.carbocene.org), engaged in research, advocacy and experimentation in rebalancing planetary carbon flux toward drawdown using the inherent leverage multiplication properties of open systems, while improving the functional and energetic connectivity of degraded ecologies.

Arcadia at the Limit

Populus tremula x alba 717 "Deer".

As the human influence on Amazonia flew under the radar of Euroamerican agriculturalists and anthropologists, so too often does the energetic reality of the climate crisis escape adequate understanding when viewed through eyes determined to separate the cultivated from the wild. All of the geoengineering methods that have potential to enable homeostatic regulation of the climate system lie across this boundary, because they all involve targeted interventions to change the parameters of planetary scale processes. In this way, a small energetic input can have an exponentially greater effect, or in other words, an intended consequence.

Ethics that place these methods *a priori* out of bounds will hobble our ability to respond as a species to the problem our own success has presented to us, because systemic changes are appraised indistinguishably from highly negative unintended consequences. Often, in a specific instance, the problem space is comparatively limited, for example, *Deer* is simply a well known variety of hybrid aspen that exhibits a more rapid carbon assimilation and therefore growth rate by a novel and evolutionarily innovative mechanism. Yes, this would result in forests in which this was the dominant species of *Populus* showing a faster overall growth rate, and therefore they would not exactly match the properties of a preindustrial forest, but we must be free to question why improving the carbon removal capacity of the terrestrial biosphere should be equated with returning it to whatever form it was in at whatever time slice our society derives its Arcadian ideal from, or some notion of a wild uncontaminated by human influence.

Every open system drawdown approach suffers from its own version of this image problem. In the case of oceanic iron fertilization, an equation with “dumping” and assumption of the inevitability of toxic algal blooms and some combination of zero effect and systemic breakdown has limited experimentation for decades. Too often, the methods of carbon removal companies are dictated by the idiosyncratic preferences of carbon markets built to reward comparatively miniscule scale removals by closed system approaches such as direct air capture, which is widely known to not be scalable in a relevant time frame to remove carbon anywhere near the rate we need, but which has the advantage of producing a product (compressed CO_2 gas) useable by the fossil fuel industry, at rates sufficient to offset the emissions of software companies.

Concepts are imported which make sense in a business context but which are entirely inadequate to the task at hand, that is, altering the control parameters of a continuous planetary flux process. A focus on permanence and traceability of specific removals to specific customers only makes sense if equal weight is given to scalability and the percentage of energy input under direct human management. Even some open system approaches have become elaborately baroque in their attempts to satisfy the demands of myopic and largely image-driven carbon credit issuance registries.

Behind all of this lies the simultaneous anxiety and reassurance of the availability of solar radiation management as a comparatively low cost solution, of a sort, should the situation continue to deteriorate without sufficient near term carbon removal. But solar radiation management solves the temperature increase problem in the near term while making other problems worse. SRM will not prevent ocean acidification, it will reduce incident solar radiation in photosynthetic wavelengths, while also removing the temperature rise control signal for carbon accumulation. At high atmospheric CO_2 levels, the therapeutic index of SRM is narrow, that is, the required annual aerosol dose falls between narrow bounds, and the consequence of underdosing in particular in a given year would be wide swings in average global surface temperature, due to the underlying climatic forcing being counterbalanced by the dimming sulfur dioxide.

Humans have the potential ability to be the first species in the history of the biosphere to enable homeostatic regulation of the carbon dioxide concentration in the atmosphere, if we abandon our desire to alienate nature from human influence, through recognizing that this is a consequence of our countervailing desire to act without consideration of the presence of living ecological systems throughout even the most human dominated environments, and to ignore our dominant influence on planetary energy flux.

The only long term solution to our spiraling negative impacts on the climate system and the functional connectivity of the global ecosystem is to work with the rest of the biosphere to create ecologies which assume the presence of human influence as a given factor. This is how the only species yet produced by the earth system to understand our own origins can open our eyes to the threads connecting us to the whole, and in doing so awaken from our Arcadian dreams to create new forests and regenerate waterways in partnership with the species surrounding us.

The only ethic that should apply here is that of systemic functional improvement in retention of energy and communication between living systems. This requires that we work with boldness in cooperation and restraint from alienation and *a priori* categorization. These attitudes have been in eclipse recently in many different contexts, but the rewards are great, no less than bringing Gaia to life through discovering and applying control inputs to planetary carbon metabolism. We would be functioning as the eyes of the biosphere seeing itself for the first time.

A Song of Deep Time

Any act of self-perception involves a certain degree of mirroring and mutual responsiveness, and our habits of othering the natural world are hard to break. The foundational shared script of all Earth organisms is written in chains of paired nucleotides. In these letters we have found written the shape and fine structure of the tree of life through deep time. Likewise the individual story of every leaf is written here, passed back unbroken to our last universal common ancestor. Anthropogenic CO_2 emission is the latest in a series of major shocks that the biosphere has inflicted upon itself in the history of its progressive integration between its own processes and those of the geosphere and atmosphere. Every one of these previous shocks ended only when new forms of organism, speaking new metabolic languages, differentiated and communicated.

The most significant step-changes in the energetic dance of Earth life have been those engendered in response to the force multipliers of the metabolic opposites of photosynthesis and respiration; first freeing life from the meager rewards of chemosynthesis and allowing the direct use of light energy to build living structure; the oxygen produced by these first cyanobacterial photosynthesizers poisoning the chemosynthetic biosphere; until life learned to oxidize biomass fuel directly in cellular respiration, this call and response creating the individuated organisms ancestral to chloroplasts and mitochondria. These both being incorporated but not consumed by a third organism contributing internal membrane bound structure, to form eukaryotic cells. And again the light eaters, first in the water and later on land, created new levels of organization; millions of cells coordinating to form multicellular cooperative organisms, both times accompanied by a shock of mass carbon drawdown, and forcing an integrative response from the heterotrophs to create structures capable of processing this biomass at scale; the multicellular animals.

It is not in any way surprising that the first organism on Earth to discover how to perform respiratory metabolism extracorporeally, in the domestication of fire, and later to feed upon the carbon fixed throughout deep time, in the combustion of fossil fuels, has caused a shock of similar magnitude to these ancient events, now caused by carbon thrown back into the atmosphere.

And now this organism, ourselves, feels the changes we have wrought. We suffer, we desire to regain stability, to keep things constant. We consult the historical records of the Earth system, and we see how in a certain respect our situation is most unusual. All prior shocks have been caused by photosynthetic organisms, or by the geosphere liberating fixed carbon in volcanic eruptions. We are the first heterotrophs to have caused an excursion of such magnitude, and at an unparalleled rate.

Although the situation is unusual, it is easy enough to see the basic outline of the answer between the lines. Yes, we must decarbonize our energy production, but this will not serve to remove what has accumulated over the last several centuries, or to reduce our global ecological dominance as energy intensive heterotrophs. We need to go talk with the autotrophs, and empower them to remove the carbon we have emitted, for all of our sake, but especially for our own. We must ask them to increase their rate of drawdown, and reduce the rate of return of the carbon they fix.

They will not do this without being asked. Increased atmospheric CO_2 deselects plants for efficiency of carbon removal; while it does stimulate growth rate, it makes metabolically expensive carbon capture optimizations like C4 less likely to evolve and spread. Increased temperature accelerates the rate of respiration-mediated decay of biomass and liberation of fixed carbon into the atmosphere, so likewise, the autotrophs will not pull this lever for us. Thankfully, most of the words are already written and we can cut and paste most of our messages together. The human discipline devoted to facilitating genetic communication between organisms is called synthetic biology, and if harmony is found in communication, it is here where we will discover Daphnis alive.

Synthetic Biology and Artificial Intelligence

For the last decade, synthetic biology has been presented as possibly affording humans a solution to climate destabilization. On its face, this statement holds as little meaning as stating, as a matter of faith, that AI will solve climate change. In the case of AI, it is possible to enumerate scenarios as to how this would occur. For example, by enabling ongoing real time adjustment and prediction of weather and user demand, an AI agent could greatly increase the efficiency of sharing of battery storage between users of electricity generated by solar arrays, and increase the rate of roll out of solar replacement for fossil fuel fired power plants. This is simply an example of one of many plausible scenarios that will, if they occur concurrently, enable AI development to, if not wholly solve, at least significantly contribute to reducing net human emissions within a relevant time frame. Importantly, this scenario must involve deployment of such agents over large portions of the electrical grid in terms of percentage energy use, to have a significant impact, and the benefit is in improved continuous cybernetic control and adjustment of energy flux within the system. As evidenced by the recent success of language models such as DeepSeek, efficient energy allocation relative to task specificity greatly reduces total energy usage.

If the same is true of synthetic biology, I should be able to generate a similar statement. There are many ways to define the discipline, but the most important shared features are that the field involves applying engineering principles to design and modify biological systems. In current surface language, the term *synthetic* refers to an imitation of a natural product, but the word has an older meaning. Synthetic materials, for example nylon, are made by the joining-together of their chemical constituents; in the case of nylon, even the name is a *synthesis* of the cities (New York and London) in which the method of manufacture was discovered. From σύνθεσις (*súnthesis*, "putting together"), we also derive photosynthetic, or putting-together-with-light. In this framing, synthesis is contraposed with analysis, or the taking apart of a whole, for varying purposes; understanding in a scientific framing, energy production in the case of respiration or fossil fuel combustion. Most fundamental to synthetic biology is the creation of new organisms, with novel genetic combinations, that would not have arisen without human intervention.

Because the Earth biosphere has existed for several gigayears, there has been sufficient time for a vast assemblage of organisms, all with their own unique method of life, to evolve. While fully analytic methods, such as sequencing followed by AI assisted protein shape optimization, hold major promise for the design of new organisms, most work in synthetic biology is also synthetic in the older sense. This is because, in all the organisms in the biosphere, there is usually some organism, somewhere, that has already solved a given problem, if often for its own different reasons. For example, in the case of photosynthesis enhancement, the genes we used came from a squash plant and a unicellular alga, while the RNA inhibitor was a mirror sequence of the tree's own glycolate transporter. The particular organisms the sequences were taken from had their own reasons for synthesizing these proteins, but their bringing together in a new arrangement in a novel organism was through human design and intervention. In decomposition resistance the synthesis was in transfer of metal accumulation ability from a plant such as creosote bush (*Larrea tridentata*), to a plant such as aspen which previously did not have this ability.

Humans have only recently developed this ability to bring together disparate, previously unconnected elements to create a new synthesis of biological properties, but the biosphere has been doing this for its whole history. To this natural synthesis we must credit such basic biological structures as the eukaryotic cell, and such difficulties as antibiotic drug resistance. To understand the latter case it is important to note that development of resistance to antibiotic drugs in bacteria rarely occurs through natural selection in the usual sense, but instead through the widespread sharing of plasmid cassettes, or fully formed genetic sequences conferring resistance, and shared for that purpose, between populations of bacteria that can be only distantly genetically related. Having explored the field we are dealing with, let us return to giving an example of how synthetic biology might help humans manage global carbon flux.

The Walled Garden

Iroko, or African teak (*Milicia excelsa*).

The African iroko tree is oxalogenic (Cailleau, G., Braissant, O., and Verrecchia, E. P.: Turning sunlight into stone: the oxalate-carbonate pathway in a tropical tree ecosystem, Biogeosciences, 8, 1755–1767, https://doi.org/10.5194/bg-8-1755-2011, 2011.); the tree secretes oxalic acid from its roots. Over time, this oxalic exudate accumulates and decomposes to calcium carbonate, or limestone, with the accompanying liberation of half its carbon as CO_2. Therefore, the soils surrounding the roots of an oxalogenic tree become enriched in fixed carbon at a ratio of half the carbon in the oxalate secreted. Oxalogenic trees are rare; iroko is one of the only well known examples, and it has a restricted distribution and a slow growth rate: it takes over a century of growth for the stem of an iroko tree to approach a meter diameter.

Synthetic biology could enable the elucidation of the oxalate secretion pathway in iroko, and the introduction of this pathway into faster growing tree species with broader climatic tolerance bands. The introduction of these trees into areas where they effectively integrate into local ecologies (likely those that match the ancestral range of the recipient species chosen), would enable an increase in the rate of carbon removal in the forests of the regions in which they were planted. Because these trees would still perform their original role, including reproducing on their own, in these ecologies, as well as removing more carbon from the atmosphere, this would enable a significant shift in global carbon flux toward drawdown. No method like this will be sufficient alone, but integrating synthetic biology with open system drawdown holds significant potential to meaningfully contribute to carbon removal.

So, like AI, synthetic biology certainly can contribute to a solution to climate change. But unfortunately, under our current regulatory framework, the methods it offers are almost impossible to test, even on a small scale. We can see this by comparing the examples; although we could explore various failure modes in which incompetent or malicious AI agents could cause, or be manipulated to cause, massive societal disruption and power outages, there is no law preventing the rollout of a test of the method. In synthetic biology, creation of a fast growing, oxalogenic tree could proceed within the walled garden of academia, but widespread deployment even of a method with demonstrable promise is almost impossible. Another example will help illustrate why.

The Salk Institute, an organization named after the creator of the first polio vaccine, and so one would think committed to significantly impacting global human problems, has spent close to two decades researching a synthetic biology innovation that increases soil carbon storage by upregulating suberin (cork) production by the roots of grasses. Field trial after field trial has been run, success has been demonstrated, but no deployment has occurred. The institute has a division dedicated to this work, the Harnessing Plants Initiative, who narrate that they have “made significant progress in the lab,” and have registered the trademark Ideal Plants. All this seeming progress obscures the fact that there is almost no viable regulatory route to widespread adoption.

Like Living Carbon’s photosynthesis enhanced trees, the Salk Ideal Plants only differ in specific respects from other varieties; in the case of the Salk plants the root system is larger, and the cork wall of each root is thicker. These differences, while specific to unusual anatomical regions, are no larger in scale than those between many horticultural varieties. They are certainly less than those between say, domesticated maize and its wild progenitor teosinte. However, the status of biotechnology regulation is such that how a thing is done carries far more weight than what it is.

It is no accident that most genetically modified organisms with legal approval for unrestricted use are bulk foods. Only agricultural-chemical conglomerates have historically had the financial and legal resources to shepherd an innovation through the arduous approval process, which can easily take over a decade, while organizations such as the Salk Institute provide demonstrations but do not assume the responsibility for deployment. Meanwhile, genetic modification of bacteria and fungi to produce drugs and foods proceeds apace and arouses little protest, and the idea of leakage of these organisms into the environment being an existential risk hardly exists itself.

Beyond the specific regulatory issue is market-driven adoption. Concern for mitigating anthropogenic carbon emissions has resulted in the issuance of carbon credits and the development of systems of carbon accounting, mostly on a voluntary basis but with increasing governmental support globally. These credits are associated with determinants of quality which stipulate conditions beyond removal of carbon. Because participation in carbon markets and the purchase of carbon credits are generally voluntary acts associated with the environmental movement, the determinants of stipulative quality of a given carbon removal tonnage include many conditions beyond verification of the removal itself. The two dominant carbon credit registries in the United States both include a stipulation that the use of GMOs for removal be prohibited for credits issued.

In the baseline public consciousness, despite a little recent progress, GMOs are still often considered a simple bad and their avoidance an obvious necessity for the ecologically literate, especially GMOs placed in natural environments such as forests. So synthetic biology methods, such as that of the Salk Institute, that have shown efficacy but would only ever work if a significant portion of photosynthetic carbon, either in agricultural or wildland systems, were fixed by their plants, are unlikely to be viable even if there were regulatory changes, without changes in public understanding. The idea of GMOs as a special danger, and the intrinsic stigma it generates, compounds on top of the general difficulty of open system approaches in gaining acceptance, to make achieving deployment of a synthetic biology mediated, open system carbon removal method a peculiarly quixotic quest, no matter how impressive any given proof of concept demonstration.

Method and Law

The idea that organisms produced by synthetic biology represent the possibility of catastrophic contamination of a previously pure biosphere has caused a strange fixation, seen both in perception and regulation, on ranking the techniques used in their production on a scale of how much impurity they introduce. The rest of the biosphere continues to communicate for its own purposes, neglecting to respect any such rules.

There are currently three dominant methods of introducing novel genetic script to a eukaryotic organism's genome; particle bombardment (adhering DNA sequences to physical carriers such as gold nanoparticles to provide mass to shoot directly into a cell), transformation using a living mediator (using the preexisting ability of organisms such as *Agrobacterium* or viruses to integrate sequences into a host genome, and replacing their genes of interest with our genes of interest), and a class of enzyme-mediated methods such as CRISPR often collectively termed gene editing. To illustrate the fixation on process over product, and of establishing a scale of relative contamination, it is telling to follow the history of biotechnology regulation in the United States since the first development of effective transformation techniques in the early 1980s.

The division of the USDA responsible for biotechnology regulation is known as APHIS (Animal and Plant Health Inspection Service). In 1987 APHIS established regulations for “the safe movement and importation of genetically engineered organisms,” simultaneously with its publication of regulations aimed to control species that spread disease. These regulations specified that *Agrobacterium*, the major organism used in plant genetic transformation, was a plant pest (correct, as it is the cause of crown gall disease in many plant species), and regulated any genetic sequence identifiable as deriving from *Agrobacterium* as being a “plant pest sequence.” APHIS went on to establish severe restrictions on import, export, trade and movement on all organisms containing “plant pest sequences.” Because genetically transformed organisms can be identified by the presence of flanking sequences derived from the *Agrobacterium* vector used in their transformation, any product of *Agrobacterium* transformation was regulated in this way.

While it could be stated that this was merely a vehicle to enable regulation of GMOs, it introduced a fixation on ‘genetic purity’ into the legal structure dealing with the entire nascent field of plant biotechnology. Other methods of transformation, such as particle bombardment, were not regulated in any way by USDA, as long as they too did not involve the introduction of “plant pest sequences,” as for example in the use of promoter sequences deriving from viruses. Although the intent was to regulate the products of biotechnology in themselves, the letter of the law portrayed the introduction of minute genetic sequences from disease causing organisms used in transformation as somehow capable of introducing the contaminating essence of the pest into the organism hosting them. The regulatory superstructure which developed therefore could be imported wholesale from existing rule systems serving to reduce the risk of spread of infectious diseases, but with a whole class of organisms transformed via non-vector mediated methods being excluded.

There are very few examples of ecological problems having been caused by genetically modified plants. Those that have happened underline the importance of separating our evaluations of technique and application. To much of society, genetically modified plants as a class are synonymous with the specific example of glyphosate (roundup) resistant crops, with the added conceptual confusion of the actual use (enabling spraying of glyphosate to kill weeds in the crop without harming it) with nebulous ideas including the production of glyphosate by the plants themselves, or simply an unknown and therefore uncanny enhancement that could escape and dominate. The problems caused by these plants are part of the general problem inherent in managing large areas of land in a manner that progressively depletes the soil biome, reduces mineral nutrients and prevents carbon sequestration. That is, they are the problems of industrial agriculture itself. Nonetheless, the historical domination of the regulatory system by the concerns of the purveyors of these plants has led to patterns of decisions by USDA illustrating the incoherence of its legislative approach.

In 2003, a creeping bent grass variety (*Agrostis stolonifera*), transformed by Monsanto to be resistant to glyphosate, for intended use on golf courses, escaped from a field trial in Oregon. The grass has since spread widely through multiple habitats across the state, and will likely continue to expand. In 2016, USDA APHIS approved glyphosate resistant creeping bent grass, claiming that it did not have enhanced weediness potential, long after it had escaped from cultivation. Creeping bent grass is a Eurasian species brought to North America during European colonization and had already shown itself capable of establishing in place of native grasses in disturbed areas, with a history of "noxious weed" classification. The intended use case for the grass was to improve the ease of weed control with roundup on golf courses. APHIS noted that "[a] primary herbicide used to eliminate CBG where it is not desired is glyphosate," but that alternate herbicides were available. Glyphosate is indeed the dominant herbicide used by ecological restorationists seeking to remove invasive plants such as bentgrass, so it seems bizarre that USDA could claim that a bentgrass variety specifically engineered to be resistant to this herbicide did not have increased weediness potential.

Noting the inhcoherence, the fact remains that roundup resistant *Agrostis* remains identical to conventional *Agrostis* in all but one troublesome aspect, and a minor threat at best. The voluminous field trial data and long timeline required for the approval stem from the intensive investigation of properties of the plant, triggered by the presence of "plant pest sequences" in the construct, although the grass was transformed via biolistics. These included "agronomic, compositional, disease and insect evaluations," for "65 field releases in 20 states and 40 counties performed between 1999 and 2002 (Scotts/Monsanto 2015a). Unsurprisingly, none of these properties differed from conventional bent grass. Glyphosate resistant creeping bent grass spreading from highly managed and intensively irrigated golf courses is hardly a poster child for integrative synthetic biology, but is more annoyance than danger.

The vast expense poured into gathering evidence to support the approval of such a marginal candidate, which was already causing problems in the wild when the decision was made, while organizations like the Salk Institute write letters to congress petitioning for funding to run the same exhaustive field trials required for approval of their plants (https://www.salk.edu/wp-content/uploads/2020/03/FINAL-Salk-ResponsetoCongressional-Select-Committee.pdf), makes clear some of the processes retarding the balanced development of plant biotechnology. Scotts/MiracleGro had already abandoned commercialization of the grass when approval was granted, and the only mention on their website now is a brief historical account and a phone number to report the grass for eradication.

After over 30 years, APHIS updated its regulations in 2020 in a piece of legislation termed the SECURE (Sustainable, Ecological, Consistent, Uniform, Responsible, Efficient) rule, replacing the determinant of regulability from "plant pest sequences" to whether a given transformation "could have happened in nature." The implication now was that 'unnatural transformations' were more dangerous and thus more regulable than those that could have occurred without human intervention.

Because living organisms exist in a context where high energy particles occasionally collide with the nucleotides in their genomes, and because the replication of these chains of nucleotides is not absolutely perfect every time, changes in individual nucleotides, including deletions, additions, and replacement of one of the four by another, are common events. These are known as point mutations. Also common are transpositions of sections of the chains, changing the order of the sequence within an organism.

The framers of the SECURE rule classified these as natural transformations, and applied minimal regulation to human methods that mimic them, known collectively as gene editing. Regulation increases as more nucleotides are changed, the reasoning being that every additional nucleotide transformed takes us further from the state of nature. Regulation is most stringent in instances where sequences from one species are introduced into another, being that this is seen as the least likely scenario to occur in nature. The organisms created by these methods are termed transgenic, as opposed to the cisgenic products of gene editing.

The recent advent of CRISPR and other methods allowing targeted single nucleotide changes at specific points in the genome has made anthropogenic point mutation relatively simple, and a gene can often be rendered inactive, more active, or have the properties of its protein product modified, by one or only a few nucleotide changes. The text of the regulation allows the stacking of repeated single nucleotide changes, so long as each stage of the project is given individual approval. But gene editing is not capable of introducing entire new metabolic pathways to an organism. These need genetic constructs enabling the production of novel proteins, either in code written by humans, or taken from a donor organism, creating a transgenic synthesis.

Gene editing is not, as usually portrayed, simply a technological advance in bioengineering that facilitates easier and safer application; it is rather a specific method that allows targeted genetic changes to small numbers of nucleotides. CRISPR will therefore never replace transgenic transformation, but rather is a complementary method. Even in instances where metabolic transformations could be achieved by specific patterns of gene editing, this would be slower and clumsier than simply introducing a construct. This is not to imply that the results of gene editing are generally less major in their effect on the organism, only that it is incomplete as a transformation toolkit. Taking a step back, we can see that what APHIS did with the secure ruling was to replace one criterion of purity “plant pest sequences,” with another “the number of nucleotides changed.” The plant biotechnology industry reoriented itself around the new measure, and immediately began to produce literature emphasizing the safety and technological advancement of CRISPR positioned as a replacement for the clumsier and more dangerous older transgenic methods. Unfortunately for the framers, there is very little that does not happen in nature, and naturally transgenic organisms are relatively common. Like other methods before, gene editing is now often used for specifically regulatory reasons, not because it is better and safer, but because it does not produce a GMO as defined by APHIS.

In December 2024, a Northern California district court vacated the SECURE rule in its entirety, granting that both the gene editing exemption and a failure to incorporate noxious weed authority were “arbitrary and capricious” decisions by APHIS. Judge Donato argued that there was no basis to assume all conventionally bred plants were risk-free, and therefore that it did not make sense to use them as a baseline to determine the scope of regulatory oversight. Additionally, the judge noted that the SECURE rule made no mention of noxious weed evaluation in regulation, weakening APHIS’ ability to determine the noxious weed potential of genetically engineered plants. With this decision, APHIS has currently reverted to the pre-SECURE rule regulatory structure, although this situation is widely considered unsatisfactory, and further revision is expected. Given that it took 15 years to update the original regulation, significant delay is likely.

I will here take the admittedly bold position that the products of plant synthetic biology do not present a unique risk, that instances of them becoming noxious weeds are possible but rare, that if this happens these weeds can and should be managed, but that a regulatory mindset deriving from ideals of purity and contamination has greatly inhibited the development of a field of knowledge and practice that represents unprecedented biospheric integration and is one of our best hopes for near term carbon drawdown. A story of four trees, all of them creations of synthetic biology, but only three with human involvement, will serve to illustrate why we are likely more scared than we need to be.

A Tale of Four Trees

Populus alba 741 “Bt”.

American chestnut (*Castanea dentata*), Darling 54/58.

Populus trichocarpa

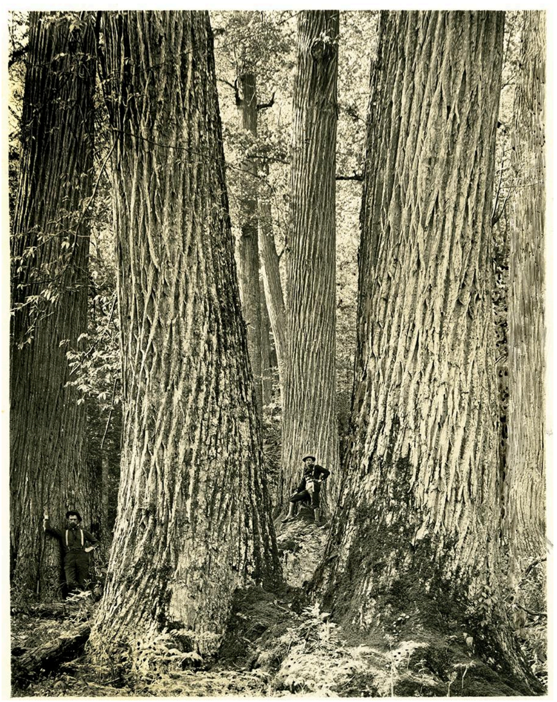
Populus tremula x alba 717 "*Deer".*

Populus alba 741 "Bt", *Castanea dentata* "Darling 54/58", *Populus trichocarpa* "BSTR", *Populus tremula x alba 717* "Deer". Four transgenic trees, four stories. The first, white poplar, with an inserted construct containing a gene from the bacterium *Bacillus thuringiensis*, producing crystals of delta endotoxin, rendering its leaves toxic to caterpillars, widely planted in monoculture forests throughout China. The second, American chestnut, with a construct containing the gene coding for oxalate oxidase from wheat, conferring resistance to chestnut blight (*Cryphonectria parasitica*), a fungus which killed 4 billion chestnut trees after introduction to North America from Eurasia in the late 19th Century, causing their near extinction and removing a previously ubiquitous species from Eastern American forests.

The third, black cottonwood containing a composite gene BSTR, composed of 3 sections pasted together. The first coding for a portion of the enzyme glycosyltransferase from the bacterium *Streptomyces*, which lives symbiotically within poplar trees as an endophyte, the second for part of a DNA-binding protein from an ant, *Trachymyrmex septentrionalis*. This specific ant is a farmer, cultivating a fungus (*Leucocoprinus sp.)* in subterranean galleries, which it feeds with poplar wood and leaf litter. The third portion of BSTR is a significant chunk of the coding sequence for RuBisCo, the carbon fixing protein in photosynthesis and the most abundant enzyme on Earth, deriving from the cottonwood's own chloroplast (which itself derives from an endosymbiotic cyanobacterium). These 3 sections, when joined together in this specific pattern, form a gene whose protein product enables the photosynthetic apparatus of the tree to adapt more rapidly to changes in light intensity, leading to significant gains in its carbon fixation rate.

The fourth tree, a hybrid of aspen and white poplar, containing a construct coding for glycolate dehydrogenase from the green alga *Chlamydomonas reinhardtii*, malate synthase from the squash *Cucurbita maxima*, and a sequence coding for an RNA product mirroring the base pairs of the RNA transcript of the tree's own glycolate transporter, reducing expression of its protein product. Together these genes instantiate a photorespiration bypass pathway, reducing energy lost when RuBisCo fixes oxygen instead of CO_2, mimicking the advantage of C4 photosynthesis, and again causing a significant increase in the rate of carbon assimilation.

The first tree seems a stereotype of a transgenic nightmare; vast barren forests of identical toxic trees, planted in swathes across Northern China at the turn of the century to bind the soil with their roots and prevent desertification. Judged according to this purpose the project has been successful; erosion has been reduced. The diversity of moths and butterflies in these forests is indeed low, as would be expected, but that of other insects is not significantly different from forests of non-transgenic poplar (Zuo, L., Yang, R., Zhen, Z. *et al.* A 5-year field study showed no apparent effect of the *Bt* transgenic 741 poplar on the arthropod community and soil bacterial diversity. *Sci Rep* 8, 1956 (2018). https://doi.org/10.1038/s41598-018-20322-3). The insect diversity would be higher in a forest with diverse tree species; these forests are barren because they are monocultures, not because their trees are transgenic.



Old growth American chestnut (*Castanea dentata*), late 19th Century.

The second tree involves a case of mistaken identity. The creation of a celebrated project by the State University of New York College of Environmental Science and Forestry (SUNY ESF), and for several years the most promising candidate for restoration of the American chestnut to its historical range, note the double name 54/58. These are trees resulting from two different transformation events. In Darling 54, the oxalate oxidase construct inserted into the coding sequence of a gene conferring tolerance to saline soils, these trees, despite being blight resistant, are therefore salt susceptible. In Darling 58, the construct did not break a gene on insertion. In both trees expression is driven by the 35S promoter, deriving from cauliflower mosaic virus, and therefore always “turned on”. Both trees therefore have a somewhat reduced growth rate.

After establishing that Darling 58 was blight resistant, SUNY proceeded to plant it in field trials and applied for regulatory approval. Unknown to SUNY, some of their mother trees were pollinated by trees from the Darling 54 line, and the seedlings planted in the field as Darling 58 were actually Darling 54. The American Chestnut Foundation pulled funding from the project upon this discovery, and also withdrew their support for regulatory approval by USDA APHIS. A few Darling 58 trees remain in SUNY greenhouses, which are blight resistant and salinity tolerant, but still have a reduced growth rate due to the use of 35S. These trees are now unlikely to ever be planted in open forests. ACF argues that their planting would be detrimental to the public acceptance of plant biotechnology, due to their reduced growth rate, also citing as a reason behind their withdrawal of funding the fact that SUNY had assigned a commercial license to an internally incubated startup, American Castanea PBC, with intent to distribute trees on a commercial basis upon regulatory approval. They argued that this was in conflict with their desire that the blight resistant tree remain in the public commons. Switching the promoter would not be a difficult task, but the withdrawal of funding and support for approval has now resulted in a politicized narrative, with the conspicuous lack of support from ACF greatly reducing the likelihood of approval.

The third tree, BSTR cottonwood, is a compelling example of the deep contingency and synthetic power of nature. That two enzyme fragments, from a prokayote and an animal, can combine with a portion of chloroplastic RuBisCo to form a composite gene integrated into the plant’s nuclear genome is already bizarre. That such a gene could be transcribed is improbable. That its transcript could be translated to a functional protein stretches credulity. That the function of this protein should be to improve the efficiency of photosynthesis itself is outside of any interpretation in probabilistic terms. With this being said, the organism is also obviously highly transgenic, and born full leafed from nature’s face. What can be interpreted probabilistically is the time frame when the event occurred.

The first wild tree discovered is almost certainly not the mother of the whole line. Black cottonwood, like most poplars, is proficient in asexual reproduction. Adventitious roots sprout easily from stem cuttings, the root system is laden with dormant buds, and regrowth from stumps and branches is rapid. Given this ability, the frequency of the tree in Pacific Northwest forests, and the comparatively recent development of human survey and sequencing techniques, the transformation event is likely to have occurred several millennia ago, assuming that the enhanced growth rate increases the likelihood of encountering a BSTR cottonwood over time. We also do not know whether the tree represents an ongoing replacement of unboosted cottonwoods, or if there are physiological costs we are as yet unaware of which select against BSTR in some environments, limiting its spread.

The question of how the event occurred must at this point be answered speculatively, but there are clues. A scenario involving shed cells in the salivary glands of ants harvesting living poplar stems or roots hosting *Streptomyces* comes to mind. Then the release of fragmented sequences during concurrent lysis of bacterial and ant cells, mixed with damaged chloroplasts, and all this happening while the genome of the tree was being actively read, perhaps during an immune response to these insect predators. Most improbable, but at least possible if repeated billions of times over millions of years, which the ongoing use of cottonwood as an ant agricultural feedstock certainly provides. Human transformation techniques such as particle bombardment, with no method to ensure genomic integration other than physically shooting the construct into the nucleus, similarly rely on this "law of large numbers," but even biolistics is likely far more efficient than whatever happened several thousand years ago somewhere near what is now Seattle.

The fourth tree, a hybrid aspen called Deer, containing a metabolic reroute first demonstrated in tobacco plants and then optimized by Living Carbon for use in trees. In the process we worked out how to grow and propagate poplar at scale in conditions that were at first challenging in terms of space and energy inputs (indoor cultivation in a converted music studio in San Francisco), and later in terms of scale and diversity of growing situations (lab, greenhouse, academic field trial, experimental forestry sites). Although demonstrating efficacy in greenhouse and field conditions and selecting the best performing event took over 3 years, we saw early evidence in our experimental *Agrobacterium* transformants from a combination of morphological, physiological and molecular measurements (Tao, Yumin, Li-Wei Chiu, Jacob W. Hoyle, Rebecca A. Dewhirst, Christian Richey, Karli Rasmussen, Jessica Du, Patrick Mellor, Julie Kuiper, Dominick Tucker, and et al. 2023. "Enhanced Photosynthetic Efficiency for Increased Carbon Assimilation and Woody Biomass Production in Engineered Hybrid Poplar" *Forests* 14, no. 4: 827. https://doi.org/10.3390/f14040827). The name Deer comes from our assignment of animal names to each clonal lineage to keep easier track of over 100 independent events.

Deer and BSTR cottonwood obtain a similar effect by differing causes. The growth rate increase is comparable, and the trees are close relatives (although these particular two have not been recorded to hybridize sexually, and are in different subgenera of *Populus*). The mechanisms operate on different branches of the energy transduction cascade of photosynthesis. BSTR better tunes its light harvesting antennae to split water more rapidly in changing light conditions, whereas Deer saves energy by efficiently completing the oxidation of glycolate produced by Rubisco oxygen capture, regenerating CO_2 within the chloroplast. Phylogenetically, the BSTR natural construct is more diverse, containing sequences from a prokaryote and an animal, whereas in Deer both genes added are from the green plant branch of the life tree. In terms of gene products, BSTR is a single composite gene with one transcript, whereas in Deer there are three transcripts produced, instantiating a complete synthetic metabolic pathway.

Behind all this lies the demonstration that, beyond the facile sense that human activity is part of the natural world, there additionally is no essential difference between a creation of synthetic biology such as Deer, and a naturally occurring event such as BSTR cottonwood. Let us then imagine a case in which there was a demonstrable slow replacement of slower growing cottonwoods with BSTR, and consider an equivalent situation occurring with Deer and wild-type aspen. While acting as agents of change should correctly lead us to a sense of responsibility toward the consequences of such change, there should be no wholesale abandonment of what from my perspective is our duty, as the bearers of intentionality and concentration of energy flux in service of this intentionality, to integrate living systems in directions that move the system as a whole toward homeostasis.

While wholesale abandonment may seem a strong term, it accurately names the central human tendency to avoid direct perception of sources of shame. If we consider shame to be an essentializing abandonment of our self-perception, avoiding perceptions that cause this becomes a survival strategy. Thinking about a constructed human world abutting upon a given natural world, without considering their inevitable intermingling, allows us to cognitively and emotionally withdraw from our contextual reality. This framing also makes it easier to externalize costs, and neglect to register energetic dependencies, while causing action paralysis even in cases of clear necessity.

This shame also bears significant responsibility for a lacuna in ecological science regarding the study of directed human improvement of ecosystemic function. Practices such as permaculture and agroforestry give hints of such a science of applied ecology, but most ecological theory still categorizes human activity as a disturbance outside the system, rather than as an inevitable component of any modern ecology that could be actively beneficial to both us and the system as a whole when managed correctly. While properties such as biodiversity are correctly seen as important to protect and restore, there is a surprising lack of theoretical undergirding to give quantitative descriptions of their benefits as general properties, or with predictive power regarding the effects of changes. We need general measures of ecological functionality, and responses to degradation that restore functionality, but in order to derive these, we must release the common assumption that restoration of function is synonymous with the restoration of some prior state of affairs. In the world as we find it, the boundaries of entire climatic zones are shifting, and the effects of humans are ubiquitous. Human assistance could enable many organisms to persist through these centuries, leveraging our intentionality in service of accelerating the evolutionary process. For example, increasing the thickness of bark of forest trees would increase carbon storage while reducing mortality from wildfires, enhancing the downy layer on the underside of many leaves would reduce transpiration rate and improve drought tolerance.

As a sketch of what such a theoretical and regulatory environment would look like for synthetic biology, imagine a world in which we had derived stable metrics of ecological functionality, using standardized data collection and measures of energetic flux. In this world, genetically modified plants would be regulated on the level of practices rather than an idea of catastrophic contamination risk. Regulatory approval could be necessary for increments of area planted, or for commercial use or use above certain production thresholds; use that would have an energetic impact. Noxious weed regulation could remain intact, and apply regardless of the construct inserted, at the level of the species worked with. To put it simply, the whole earth is already our garden, it is high time we recognize this and treat it so.