ELEMENTA
Science of the Anthropocene

Montenegro de Wit, M, and Iles, A. 2024. The Evidence Project: Genetic (geo)engineering in a climate-changing world. *Elem Sci Anth*, 12: 1. DOI: https://doi.org/10.1525/elementa.2024.00005

RESEARCH ARTICLE

The Evidence Project: Genetic (geo)engineering in a climate-changing world

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As agroecologists worldwide explore pathways for food systems transformations, "evidence" is in high demand. But what is evidence? How is it used? By whom and for what audiences? What does evidence support and why? We contend evidence is inherently political and thus *relational*. In our article, we connect Science and Technology Studies (STS) scholarship on evidence with critiques of colonialism, capitalism, and empire, offering a framework to analyze evidence via interlinked levels of practice, political economy, and ontological foundations. Reviewing 3 historical waves in scientific and technological (S&T) evidence, we show how the production and use of evidence has evolved within the capitalist and colonial/modern world to imbue specific food futures with legitimacy and power. We then turn to our case: gene editing of crops for carbon drawdown. Over the past 5 years, university researchers, start-ups, governments, and intergovernmental agencies have asserted that gene-edited crops will sequester carbon, benefit farmers with nutrient-rich soils, and save Earth from runaway climate change. What evidence do they offer? Using the Salk Institute's Harnessing Plants Initiative (HPI) as an example, we explore how HPI generates and uses 3 main types of evidence—institutional and human evidence, scientific and technical evidence, and financial/economic evidence—to identify problems, propose solutions, attract funds, and make plans to scale technologies worldwide. We then analyze the political economy factors that drive the production of HPI evidence and the assumptions about evidence etched into its colonial/modern worldview. A relational evidence approach, we find, illuminates how elite actors mobilize resources to actualize futures for which empirical evidence today is thin. Finally, we suggest strategies agroecologists might pursue in a pluriversal transition toward multiple evidentiary terrains: "a world of many worlds" for knowledge, land, and life.

Keywords: Gene editing, Climate, Evidence, Colonialism, Coloniality/modernity, Agroecology, Food systems

1. Introduction

Over the past 20 years, agroecologists worldwide have moved from simply redesigning farming practices and farming fields to demanding systemic food system change (Méndez et al., 2013; Mier y Terán Giménez Cacho et al., 2018). As many researchers and practitioners have learned from movements that what happens on a farm shapes, and is shaped by, the politics and political economy of larger food system structures, their appetite has grown for exploring pathways and processes for transformative change. Many different analytical approaches are being tried out. For example, Titonell (2019) portrays agroecological transitions as a sequence of emerging innovations at multiple scales: technical-productive change at farm level, socio-ecological change at the community level, and political-institutional change nationally. Anderson et al. (2019) discuss how agroecological transitions can be accomplished through addressing, disabling, and enabling conditions across 6 domains of transformation, including discourse, knowledge and culture, and access to natural ecosystems. Within these transition debates, a key problem is how to tell whether change is truly agroecological and transformative in character. Here, for example, Giraldo and Rosset (2023) urge emancipatory agroecologies—"radically transformative processes that take place within collective struggle"—instead of what they label as neoliberal and reformist agroecologies that reinforce dominant market-based or top-down government-led models. They delineate 6 social principles—such as cultivating autonomy, not dependency—to distinguish between transition pathways, using empirical evidence to test a particular trajectory.

Agroecologists are also experimenting with ways to discursively justify transitions to diverse actor groups, from policymakers to farmers. They are endeavoring to open new space for agroecological knowledge in the face of hegemonic capital-state interests and monopolistic agri-food firms that have reshaped much of the planet in their pursuit of money and power. Evidence has

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become central here. Sizable agroecological evidence is now being generated worldwide in the hope of convincing societal actors of agroecology's viability. Thus, the past few years have seen expert reports comparing the evidence for different sustainability and food security approaches (High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security [HLPE], 2019); "rapid evidence reviews" by scientists of agroecology's climate adaptation and mitigation potential (Snapp et al., 2021); and case studies from movements and nongovernmental organizations (NGOs) that provide practical evidence-based examples. Together, these efforts represent both material assessments of evidence and bids to participate in the growing discourse of evidence—on the assumption that doing so will support a transformative agroecology. In the words of the Alliance for Food Sovereignty in Africa (AFSA), "There is an avalanche of evidence coming from almost everywhere in the world that agroecology works and this is Africa's contribution to changing the narrative of industrial agriculture with evidence from the ground" (AFSA, 2016, p. 5).

However, even though agroecologists frequently invoke and mobilize evidence in these ways, they have devoted relatively little attention to the politics of evidence. What *is* evidence? How is it used? By whom and for what audiences? What does evidence support and why? If agroecologists are not reflexive about the evidence they make and use—and about the evidence that they are trying to challenge—they can reproduce the norms and standards of colonial-modern science and technology that, under capitalism, devalues certain lives and knowledges under the aegis of efficiency, progress, and development. Agroecologists can also struggle to gain real traction in their calls for transformative agroecology when venture funds, technology companies, and international organizations brandish "sustainability" in their visionary plans for transforming the food system. Despite their best intentions, agroecologists may find themselves being pulled into what Giraldo and Rosset (2023) call neoliberal and reformist agroecologies, due to funding opportunities, institutional recognition, and other incentive structures. Interrogating evidence, then, is central to avoiding the pitfalls of reformism on the path of emancipatory change. To be clear, we are not suggesting that transforming food systems is merely a matter of producing evidence. Societal ruptures recognized as liberatory, emancipatory, and revolutionary have historically required struggle through crisis, protracted violent and nonviolent resistance, and a process by which people come to reject the basis of the social order they live under—and to imagine and create alternatives. What we *are* suggesting is that evidence is a key terrain on which these struggles occur. Asking about the politics of making evidence opens a window onto how communities diverge or converge in their understandings of nature, labor, care, capital and how the material relations of the living world connect to the epistemic and ontological foundations by which we define who we are, what life is, and what it means to "sustain."

We contend evidence is inherently political and thus *relational*. Conventionally, evidence means the information generated for and introduced in argument or dialogue to prove—or rebut—a proposition as "valid" or "acceptable" within the analytical standards of a particular domain, such as science, law, or public policy (e.g., Majone, 1989). However, evidence does not simply exist to be stacked like weights on a scale, eventually tipping one way or the other. Nor is it something objective and neutral. As scholars working in Science and Technology Studies (STS) have long shown, evidence is socially constructed, reflects policy and institutional framings, and serves in democratic polities as a site for ongoing disagreement. Thus, evidence needs to be analyzed as a nexus of power relations (political-economic, epistemic, ontological) and in terms of the *longue durée* processes through which evidentiary strength emerges.

In this article, we connect STS scholarship on evidence with critiques of colonialism, capitalism, and empire. Global South scholarship has identified a potent mechanism through the twining of "modernity" and "coloniality." Initially developed by Anibal Quijano (1991; 2007), colonial/modernity is founded on the notion that the freedoms, prosperity, and scientific promises of modernity depend on, and are generated by, the destructive, exploitative, and carceral violence of coloniality (Quijano, 2000; Chakrabarty, 2008; Underhill et al., 2023). Colonial/modernity is also constantly under threat from decolonial and anticolonial struggles that have fought the destructive logics of settler-state formations backed by imperialism, militarism, and border violence. Scholars have extensively chronicled how social movements have resisted colonial-capitalist extraction and enclosure (and thus, the "cheapening" of bodies, care, labor, and nature); refused logics of hierarchy (and thus, anthropocentrism, white supremacy, and patriarchy); and revived, or kept alive, relational ways of knowing and being rooted in collectivity, continuance, interdependent survival, and radical care (Abunimah, 2014; Patel and Moore, 2017; Simpson, 2017; Arora and Van Dyck, 2021; Barakat and Hayes, 2023).

To understand how evidence is now being used within the colonial/modern world to imbue specific food futures with legitimacy and power, we look to a different field from agroecology: gene editing for carbon drawdown, or what we dub plant genetic geoengineering. Over the past 10 years, university researchers, start-up firms, governments, and intergovernmental agencies have increasingly asserted that gene editing will both enable crops[1] to mitigate global carbon emissions and help farmers adapt effectively to climate impacts such as drought and heat. Plants, they suggest, can be gene-edited to absorb carbon in their tissues and in soils at scale. Photosynthetic inefficiency can be repaired to speed growth and boost biomass and yield. Nutrient content can be enhanced to offset diminished nutrition. Torrents of philanthropic and venture funding and institutional support are pouring into this nascent scientific and technological R&D arena. The San Diego-based Salk Institute has received over $130 million for its work on potential soil carbon sequestration, while the Audacious Project (primarily funded by Silicon Valley business figures)

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[1] Researchers are also working to gene edit farm animals and birds that can better survive heat and other climate effects. We do not examine these organisms in this article.

alone has bestowed $70 million on UC Berkeley's Innovative Genomics Institute, partly for similarly speculative agricultural research. Meanwhile, agroecologists have advocated for the immediate, already-existing climate benefits of practicing agroecology (e.g., Altieri and Nicholls, 2017; Snapp et al., 2021)—yet funding and legitimacy for this work remains meager (e.g., DeLonge et al., 2016). While underinvestment in systems that threaten dominant interests should come as no surprise, the evidentiary strategies by which this delegitimation and de-development occurs is worth studying. Whereas investors spin agroecology's evidence as an anachronistic return to an agrarian past, they typically gloss the still-thin evidence for gene editing, extolling instead its promise for the future.

Our article is structured as follows. We begin by developing a relational approach to the production and use of scientific and technological (S&T) evidence. Next, we periodize a brief history of S&T evidence—and resistances to it—within the making of the modern world. Together, this relational, historical framework (Schiavoni, 2017) helps us to study contemporary politics and practices of evidence-making. After sketching our methods, we turn to examine genetic geoengineering in agriculture. We focus on the Salk Institute's Harnessing Plants Initiative (HPI) as a case to explore how Global North researchers generate and use evidence to identify problems, propose solutions, attract funds, communicate with policymakers and publics, and make plans to roll out their new technologies across the globe, with significant repercussions for agrarian communities. Finally, we discuss what it may look like to expand evidence beyond the colonial/modern world, toward an agroecological pluriverse of evidence(s).

2. A relational approach to evidence

As any encyclopedia entry about evidence attests, the notion of "evidence" contains multiplying definitions and applications, with debates going back for millennia. Epistemologically, evidence works as a *means* of supporting or undermining something, which can be a knowledge claim, belief, everyday practice, political action, technology, government policy, scientific hypothesis, or legal charge. Evidence is commonly thought about as a professional or technical practice, but it pervades our lives, from watching how other people behave to asking doctors why they recommend a treatment. Decades of scholarship in STS demonstrate that evidence is socially constructed. Evidence is also contingent: it can take diverse forms worldwide according to local histories, cultures, and environments. What evidence means, how it functions, who makes it, and for whom will also depend on the specific field and/or arena in which it is produced and used.

As the sociologist Mustafa Emirbayer argues, a relational lens more accurately captures the social world than a static mechanistic approach. He defines "relations between terms or units as preeminently dynamic in nature, as unfolding, ongoing processes rather than as static ties among inert substances" (Emirbayer, 1997, p. 289). Jasanoff and Wynne (1998) describe how technical experts and policymakers tend to frame the flow of science to policy as linear and unidirectional. Scientific and technical evidence is produced, verified, recognized, and used to speak truth to power. However, far from scientific evidence merely feeding into policymaking, policymakers actively alter evidence through imposing legislative mandates, choosing to reject what science says, and/or accepting industry lobbying to change evidential rules. Scientists in regulatory advisory committees may engage in contentious disputes about what the evidence says, and whether enough evidence exists to justify government intervention, thereby turning into policymakers (and thus audiences) in their own right (Jasanoff, 1990).

Extending STS scholarship on the constructed nature of science, and thus evidence, we offer the following framework to analyze evidence in terms of 3 interlinked levels of practice, political economy, and ontological foundations.

2.1. Practices of evidence

Evidence is not a fixed concept but depends on the specific field of science or practice. Science, law, practice-based productive sectors, politics, and civic/public life have their own historically accreted rules and criteria for evaluating evidence and its strength. For instance, scientists tend to take a probabilistic approach to determining whether a hypothesis is "correct," rooted in verifying via peer review that the appropriate scientific methods have been followed. Even within science, a tremendous variety of evidential standards and practices exist, from those prevailing in ecology to those favored in neoclassical economics (Galison and Stump, 1996). Some disciplines rely on experiments while others use field investigations and still others draw on models. In contrast, lawyers use legal precedents to decide what, if any, evidence can be admitted into a courtroom and seek to meet the burden of proof, which in criminal prosecutions is deemed to be "beyond all reasonable doubt."

Evidence is shaped both by producers and receivers, as it is always generated for particular audiences with the aim of persuasion. STS scholars have demonstrated this interactivity between makers of evidence and audiences whose logics, expectations, and interpretive work recursively shapes whether, what, and how evidence comes into being (Jasanoff and Wynne, 1998; Jasanoff, 2004). Evidence emerges as part of a debate or dialogue between producers and audiences. It can be used to fight evidence that other producers make. Lawyers, for example, generate litigation evidence for courts from plaintiff and defendant perspectives; policy analysts make cost–benefit studies aimed at legislators and publics who may be unenthusiastic about embracing a proposal; companies work to convince regulators and consumers their products are safe, while NGOs argue against this. Thus reception matters: Will the audience find a particular piece of evidence more or less strong? Can this audience be convinced or dissuaded? Conventionally, this will depend on the credibility tests to which an audience subjects evidence.

Different actors within complex social systems like agriculture often recognize particular kinds of evidence as more credible and legitimate than others (Montenegro de Wit and Iles, 2016; Iles et al., 2017). These kinds coexist and can come into conflict as actors engage with one another. Industrial agriculture illustrates this diversity and tension. For example, agronomists emphasize field counts of crop yields, soil fertility, and water retention. Ecologists favor quantitative and statistical data that indicate cover cropping nourishes underground microbial diversity. Bankers look for signs that a farm enterprise is profitable and can repay debt. Investors search for indications that a new start-up offering a robot harvester can readily be scaled up into a successful business. Even among farmers, an extraordinary diversity of engagements with evidence exists (Carolan, 2006). Some farmers prefer evidence they observe through their senses or experiences, learn about at farmer field days, or absorb from other farmers they trust. Other farmers may be more willing to accept claims communicated by trusted technical advisors, such as extension staff or agrichemical agents. Social movements may draw on experiential, economic, and ecological data to expose the ailments of industrial farming. Within the agricultural arena, then, many kinds of evidence are circulating and may matter in different contexts.

2.2. The political economy of evidence

Evidence supports or constrains the flow of value. In the dominant political economy of capitalism, this means that evidence—and who controls evidence—is tightly bound up in systems of surplus value extraction from labor (general accumulation), de novo separations of people from natural and social wealth (primitive accumulation), and multiple spatial and social "fixes" to contain the contradictions of capital. As global capitalism evolved from feudalism as a strategy to reassert power of the ruling class through new divisions of labor and new forms of theft, imperialism and colonial capitalism carved deeply uneven spheres of exchange onto world regions where land dispossession, ethnic cleansing, and genocide had already marked the "uncivilized" world as the place from which wealth rightly flows.

Evidence is epistemologically and materially shaped by this context in several key respects. One is through unequal exchange. The de-development of global regions through colonialism and empire has slowed the advancement of science, technology, and industry relative to the EuroAmerican/Anglo world (Ajl, 2021). It has included International Monetary Fund (IMF) and World Bank packages that saddled countries with insurmountable debt and that privatized, via structural adjustment policies, innumerable spheres of knowledge production and labor in which evidence circulates and out of which evidence grows. Among these, agriculture has undergone transformative shifts, especially where privatization of land, water, and seed, trade liberalization, and Green Revolution interventions combined to erode agrobiodiverse production systems and the practices that sustain them (Zimmerer, 2015; McMichael and Weber, 2022). While countries across the Global South have had heterogenous and particular experiences with development, their people's capacity to make and use evidence cannot be understood outside of class struggle defined by the development of their productive forces in conjunction with patterns of ownership of their means of production (Cabral, 2016 [1966]). It also means that liberatory development trajectories are possible, which would support endogenous and Indigenous knowledge systems and, thus, other bases of evidence.[2]

The political economy of evidence we refer to is not only about development but also about innovation as a commodity. As many scholars have documented, innovation does not occur in a vacuum of scientific genius but deeply depends upon money power, including funding from governments and private sector capital (Mazzucato, 2013). Silicon Valley has become a crucible for driving innovation. For firms, investors, and neoliberal governments, "real" innovation occurs through the emergence and rapid expansion of technology companies as they remake markets around new technologies, rather than traditional manufacturing industries like steel and chemicals. This standpoint is not homogeneous; many regions and countries (e.g., China, Germany, and Japan) still prioritize their manufacturing sectors. Yet the influence of Silicon Valley is palpable globally; it means companies today often sell "new" products that are only marginally better than their last versions—a new iPhone with a different number, a slightly better camera, and always a higher price—while leaving socially relevant problems (like climate change, global hunger) largely untouched. This political economy of innovation, critics suggest, has managed to narrow innovation to mean technological innovation, harnessing discourse of the future largely to maintain stability and *avoid* change despite the transformative rhetoric (Niedermeyer, 2019; Marx and tante, 2024). Financialization has meant historically unprecedented sums of money being "created" through technology stocks and hedge funds, which in turn cycle back into further frantic experiments with innovation. Thus, evidence increasingly follows, and upholds, the visions of technology companies.

Finally, concentration of power by corporations, states, and elites has the capacity to shape the scientific R&D upstream from production of evidence to manipulate the interpretation of evidence for political purposes, to leverage media to amplify evidence, and to disavow and ignore counterevidence from communities and publics. Energy politics over the past 120 years illustrate how evidence has been tightly entwined with the global fossil fuel industry. Mitchell (2013) shows how fossil fuel companies have a history of sabotaging elements that imperil their control over production, and evidence has long been a part of this story. In the early 1900s, the oil industry limited information about where reserves existed and in what quantity, to secure an oligopolistic market position and to maintain underdevelopment in some regions. We now know that oil firms have systematically manipulated scientific evidence regarding climate change since the 1970s (Supran et al., 2023). The oil giants today face numerous

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[2] Egyptian ecologist and economist Ismail Sabri Abdullah famously warned that liberation should not be reduced to "development," nor development to "industrialization" (Ajl and Estes, 2024). Yet development in a framework of *liberation* is possible, and as Cabral continually emphasized, must involve liberation from the grips of monopoly capital and restoring people's control over their territory. These material conditions are prerequisites for pluriversal evidence-making, as we discuss in Part 7.

lawsuits for allegedly lying to governments and the public about climate change, including an action launched by the State of California in September 2023.

2.3. The colonial/modern world

For the past 600 years, science, law, and civic institutions have been built by imperial powers in their conquests of land, dispossession and genocide of Indigenous peoples, and epistemicides touted as making the world "modern" (Grosfoguel and Cervantes-Rodríguez, 2002; Bautista, 2014). Since the papal decree of 1455—the so-called "Doctrine of Discovery"—anointed European Christians with the rights to conquer Saracens (Muslims), Africans, Indigenous peoples, and all other "pagans"[3] colonial doctrine has been exported around the world, enslaving racialized subjects, outlawing languages, and committing land theft by policy decree, occupation, and forcible dispossession. As capitalism emerged within the racial ideologies and juridical-political frameworks of colonial empire, it birthed a system of capitalist relations in and through colonial networks of commodities, peoples, ideas, and practices, which formed a planetary web of value chains connecting multiple and heterogeneous sites of production across oceanic distances (Amin et al., 1982; Ince, 2018; Marya and Patel, 2022). Colonialism thus underpinned the rise of racial capitalism in the long 16th century (Burden-Stelly, 2020), extending racialism into "the larger tapestry of the modern world's political and economic relations" (Robinson, 2000 [1983]).

Many scholars have chronicled how this system, as an expression of imperial power, underwrote the mass genocide of Native peoples across Turtle Island beginning in the 16th century; legitimized the Transatlantic slave trade from the 16th through the 19th centuries; actively underdeveloped the continent of Africa across this same era; and formed British colonial policies in India where over 100 million people died between the 1770s and 1940s (Amin, 1972; Rodney, 1972; Mintz, 1985; Trask, 2004; Coulthard, 2014; Davis, 2017). Agrarian Marxists such as Amílcar Cabral have analyzed colonialism and neocolonialism in terms of their shared essential characteristic of imperial domination: that is, the negation of the historical process of dominated people by violently usurping their freedom to develop national productive forces (2016 [1966]). Black feminist scholars like Sylvia Wynter have, in turn, argued that the very construct of "human" reflects the ongoing imperative of securing the well-being of a narrow ethnoclass (Western bourgeoisie) conception, on whose basis the world of modernity was propelled into existence, but "which overrepresents itself as if it were the human itself" (Wynter, 2003). Importantly, however, modernity's foundational progress narratives and its conviction of its own universality require these ontological, epistemic, and material violences to be erased, relegated to history, or seen as aberrations (Underhill et al., 2023).

The codification of evidence by institutions rooted in this world thus reflects dominant frameworks of universal knowledge as a means to index and control life, to support the project of settler-statehood, and to undergird racial-capitalist accumulation (Dussel, 2000; Melamed, 2011; Stein, 2019). Evidence is onto-epistemological, reflecting categories of being, thinking, and relating that coloniality/modernity renders universal, but which actually reflect a narrower set of EuroAmerican worldviews, where civilizational progress hinges on conformity to its matrix of hierarchical assumptions and the violences they generate. This also has significant repercussions for understanding where and on whose terms evidentiary struggles in food systems can be waged. The terrain of colonial/modern ontologies remains an important battleground, primarily because it constitutes the majority of formal Western science and law, and marshaling evidence in this space is a keyway of leveraging resources for, and legitimizing, reforms that, over time, may amount to transformative change.

3. A short history of S&T evidence

In this article, we focus on S&T knowledge as a particularly potent form of making evidence. Such knowledge has gained a uniquely privileged status in modernity's concept of civilizational progress, upheld by social, institutional, and political-economic domains in the Global North—and serving as a central pillar in its civilizing mission of the Global South (Mignolo, 2011). Haraway (1988) called this modernizing and patriarchal view the "God Trick," an omniscient perspective that achieves the aura of universality and neutrality, belying its basis in a singular, partial standpoint (see also Harding, 2007). The god trick is also self-actualizing, as claims to universality, backed by colonial force, provide S&T evidence with the ability to travel between disparate domains and across geographies worldwide (Latour, 1986; Prakash, 1999; Seth, 2009). The exceptional authority thus gained is not only because of its perceived objectivity but also because S&T is now ideologically and materially embedded in *how* institutions and publics globally think and operate.

Such embeddedness is neither static nor complete, however, which is why we turn to analyze evidence through a conjunctural lens[4]: as a phenomenon that

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[3] "We [therefore] weighing all and singular the premises with due meditation, and noting that since we had formerly by other letters of ours granted among other things free and ample faculty to the aforesaid King Alfonso—to invade, search out, capture, vanquish, and subdue all Saracens and pagans whatsoever, and other enemies of Christ wheresoever placed, and the kingdoms, dukedoms, principalities, dominions, possessions, and all movable and immovable goods whatsoever held and possessed by them and to reduce their persons to perpetual slavery, and to apply and appropriate to himself and his successors the kingdoms, dukedoms, counties, principalities, dominions, possessions, and goods, and to convert them to his and their use and profit" (The Bull Romanus Pontifex (Nicholas V), January 8, 1455).

[4] Stuart Hall is one of the most adept practitioners of conjuncturalism. When he died in 2014, many tributes noted his emphasis on the "conjuncture" or "getting the analysis right." While we have no pretense in this article of getting the analysis "right," we are motivated by what this approach affords. Conjunctural analysis can be defined as "the analysis of convergent and divergent tendencies shaping the totality of power relations within a given social field during a particular period of time" (Gilbert, 2019).

co-constitutes salient features of the moment (the Enlightenment, Cold War, climate change) interacting with *longue durée* forces of history (colonial-modernity, capitalism, etc.), and in which dominant systems of knowledge always generate evidence in response to social-ecological resistances, and vice versa. Drawing on STS and history of science scholarship, we review 3 major historical waves in the formation and use of S&T evidence.

3.1. The enlightenment wave

From the 15th century, the cognitive and political foundations of Western science were gradually built through strengthening reverence for empirical evidence generated and evaluated according to scientific methods. Early European advocates, like Francis Bacon, proposed that empirically tested evidence as a standard of proof was intrinsically superior to, for instance, priestly sagacity (Merchant, 1980). Mathematical measurement and new observational devices became central to such empiricism. STS scholars often invoke the controversy between British natural philosophers Robert Boyle and Thomas Hobbes over Boyle's air pump experiments in the 1660s as an archetypal example of how "science" acquired the authority to speak for and about "nature" (Shapin and Schaffer, 1985). The air pump—a suction device attached to a glass bulb that could contain different objects—was symbolically mobilized by Boyle's allies in support of this newly emergent experimental science. A series of trials took place under varying conditions to explore this suctioning device (or what scientists now call a "vacuum") and to settle an emergent debate: Boyle argued that evidence could derive from the public witnessing of experiments and communication of results as detailed written experimental reports that in principle would permit others to replicate the test and thereby become experiential witnesses. Hobbes, by contrast, rejected the idea that natural philosophy could be divided from politics and religion, argued that the air pump lacked physical integrity, and assailed the ability of experiments to engender consensus on the truth. He insisted that evidence came from definition of concepts and philosophical analysis, rather than from untrustworthy sensory observations of "facts."

The Boyle/Royal Society coalition prevailed, largely because its private, expert-centered approach to knowledge-making gained greater traction in dominant Restoration-era British political institutions (Shapin, 1996). In their conception, systems of human thought and action remained "practical arts" with no sustaining body of scientific theory to ratify them. They formalized a distinction between, on one hand, the technical knowledge of elites—generally sons of aristocrats—who were granted the authority of "experts" and on the other hand, the common-sense "know-how" of peasants and artisans, who were not seen as credible witnesses in the creation of knowledge (Wakeford and Sanchez-Rodriguez, 2018). Science, in theory, offered a model for how societies could be peaceably governed: It eschewed war in favor of managed conflict, self-disciplined free men acting rationally, and a peaceful community without arbitrary control.

The conception of evidence as "apolitical" and "ahistorical" also resonated with a wider colonial capitalist mindset that cleaved Europeans from nature and subordinated humans as they joined colonial expeditions around the globe (Patel and Moore, 2017; Ghosh, 2021). In this era and well into the 19th century, S&T evidence was fundamental in assisting plantation design: on cotton, coffee, and sugar plantations across India, the Caribbean, Brazil, and the U.S. South, bureaucratic technologies enabled surveilling, recording, and managing enslaved Black and Brown workers (Browne, 2015; Whittaker, 2023).

Early scientists battled over what would count as evidence, but they represented a white, male, European, and affluent community. Indeed, the idea that S&T were among the gifts that Western imperial powers brought to their colonies was an integral part of the "civilizing mission" discourse—one vaunted by both proponents and critics of the methods of colonialism (Seth, 2009). Scientists spoke to, and affirmed, the knowledge of privileged classes as opposed to workers, farmers, women, and racialized groups whose knowledge was deemed illegitimate. Many did not recognize, or perhaps even know about, the vast body of non-Western science and investigation beyond European borders: in China, India, Africa, and what is now called the Middle East (Said, 1978; Dussel, 2000; Grosfoguel, 2013). The Eurocentric nature of Enlightenment thought is commonly eclipsed in dominant narratives of "revolutionary" scientific exceptionalism. Yet the ascendant role of evidence was to successfully establish a narrow vision of experimental truth and to buttress the power of scientific institutions alongside empirical natural philosophers (Shapin, 1996).

3.2. The scientific order wave

Between the 1830s and 1960s, an international scientific order coalesced, predicated on production and use of S&T evidence as *the* basis of civilization and prosperity. Legitimate evidence-makers remained white, male, European, and wealthy, but expanded to include inhabitants of the colonial-settler states of North America and Australia. Nation-states across the Global North solidified their new government institutions through statistics, maps, surveys, and censuses—evidential artifacts to know about and govern their growing populations (Skocpol, 1995; Porter, 1996; Scott, 1998). Imperial authorities applied similar techniques to control their colonial territories and resources. Britain built a large bureaucracy stretching from India to Kenya, gathering intelligence on "natives" (who often rebelled) and calculating how much wealth it could extract from its colonies (Baber, 1996; Simpson, 2021). This wave also prompted a colonial scientific enterprise that sought S&T evidence across the planet, through specimen collecting expeditions, tropical field stations, and agricultural research institutes (Kloppenburg, 2004; Naylor and Schaffer, 2019). Globally, the period was defined by the construction of large-scale modernization projects such as dam-building and electrification (Goldman, 2005), and by the formation of industrialized democracies around fossil fuel extraction (Mitchell, 2013).

By the mid-20th century, a stable "order" seemed to have diffused among scientific institutions across the

Global North. This order relied on evidence that was standardized, upheld a humanistic ethos in a Cold War world, and reinforced the postwar liberal Bretton Woods regime. Such an order embodied the cultural norms and practices of the most dominant disciplines, especially physics and chemistry. Inside this world, evidence had to conform to specific formats and kinds (e.g., quantitative, experimental, p-testing via statistics), with others being excluded as "unscientific." French sociologist Bruno Latour and other ethnographers have traced how this evidence took form and acquired credibility via what happened in laboratories, field stations, and habitats (Latour and Woolgar, 1979; Doing, 2008; Henke, 2008).[5] The evidence could be verified or disputed by others in peer review mechanisms, adding to an accumulating body of recognized knowledge. Robust evidence could theoretically be reproduced by different scientists in many locations. This made evidence universally true, capable of traversing vast geographic and social distances—something that the mid-20th century S&T regime took for granted.

As in the earlier era, 20th century science provided a model for how human societies ought to be run. Now, however, instead of individual gentlemen scientists touting reason and self-discipline, it was leading scientist-bureaucrats who promoted a "scientific culture" for bringing peace and growth to a war-wracked world. In the postwar period, Vannevar Bush argued that basic research was "the pacemaker of technological progress" (Bush, 1945) and called for founding the National Science Foundation (NSF) to award peer-reviewed grants. The 1950s saw numerous enthusiastic projections: Science would lead to flying cars, all-plastic houses, limitless atomic energy. Science also bestowed a humanistic veneer on geopolitical Cold War projects such as the Green Revolution, in which the Rockefeller Foundation and U.S. government introduced high-yielding seeds (HYVs), fertilizers, and pesticides to low income countries to quell social unrest and defuse the perceived communist threat (Perkins, 1990; Patel, 2013).

From the 1920s, especially in the United States, scientists began to take on advisory roles, traveling widely beyond their technical communities to communicate evidence to policymakers, legislators, judges, and businesses, and even making policy themselves. Scientists portrayed themselves as—and were taken for—impartial testifiers on what science said about nature and humans. The fact that many scientists were taking money from industry and conservative interests to provide evidence sympathetic to their positions was obscured until much later (Norton, 2008; Markowitz and Rosner, 2013; Oreskes and Conway, 2023). Scientists also led numerous R&D efforts in corporate and military laboratories. From the 1940s, huge military investments in intelligence and information technologies kick-started the drive toward mechanized computing. The space race was perhaps the most notable Cold War contribution to globalized data systems and practices, particularly satellite technology (Leonelli, 2019). By the end of this era, S&T evidence had come to define modern Global North nation-states, through its wide—and frequently mandatory—use in regulatory science, technical administration, and the legal system (Jasanoff, 1990; Jasanoff, 1995; Porter, 1996). The travel of science meant that S&T evidence increasingly did not simply reflect scientific methods but an array of regulatory, policy, legal, and other institutional influences, which effectively shaped what "legitimate" evidence comprises, how it is produced, and for which purposes (Jasanoff, 2004).

3.3. The neoliberal science wave

From the 1940s onward, decolonization movements began to contest the idea of science as a civilizing enterprise that brought peace instead of a rapacious colonialism. Fanon's writings, for example, made clear that "evidence" for state-sanctioned barbarism could be found in medical officials and psychologists playing an integral role in the pathologies of a dying colonialism (Fanon, 1961). Even while new social classes emerged to drive wedges between rural laboring masses and urban foreign agents of domination (Cabral, 2016 [1966]), evidence was no longer stabilized by paternalistic dictates of empire. Movements in Mexico and India simultaneously began to gather evidence to challenge the World Bank, Rockefeller, Ford Foundation, and the United States in Green Revolution agricultural interventions (Shiva, 1989; Wright, 2005).

Meanwhile, in the imperial core, community groups, citizen scientists, and social movements began contesting S&T evidence by critiquing its biases. Inspired by, and sometimes in partnership with, Indigenous communities, grassroots science began to recognize and legitimate non-Western ways of knowing and intergenerational knowledge transmission (Gonzalez, 2001). Community groups created alternative scientific methods—like popular epidemiology, "bucket brigades," and citizen science—resulting in vernacular forms of evidence to prove the existence of pollution, toxic risks, and health impacts that dominant scientific and policy institutions had dismissed (Brown, 1987; Corburn, 2005; Iles, 2007; Brown et al., 2011). Groups like Science for the People emerged from the anti-Vietnam War movement to contest the militarization of scientific research, the corporate control of research agendas, the environmental consequences of energy policy, and more. Makers and types of evidence thus proliferated, and evidence was leveraged in resistance to dominant standpoints. Critiques of "undone science," or areas neglected in scientific investigation due to lack of interest or funding, emerged from NGOs (Frickel et al., 2010).

This struggle against terms set by Western Science reinvigorated earlier anticolonial organizing across the Global

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[5] A rough schematic might be as follows: Scientists propose a hypothesis that builds on or challenges knowledge in their fields; carry out experiments, tests, trials, or field observations, often using technical apparatuses; generate, process, and visualize raw data; apply agreed-on analytical methods such as statistics; transform the data, methods, and findings into inscribed form (frequently a peer-reviewed paper, an early view paper, or a conference talk); and communicate the inscription to their peer community through publication or conference presentations (see also Latour and Woolgar, 1979).

South, as groups fought against multinational firms bearing GMOs and pipelines, domestic bureaucrats importing doctrines of modernization, and a World Trade Organization intent on codifying intellectual property rights globally (Cavanagh et al., 2004; Kinchy, 2012). Simultaneously, in the research space, some sciences began accepting *normative* evidence as legitimate: conservation biology, for example, emerged in the 1980s to produce evidence in support of sustaining biodiversity. In this sense, the Royal Society's grip on evidence as empirically objective was loosened by popular resistance, by scientific dissidents, and by disciplines unafraid of partiality, enabling evidence to better respond to social concerns.

In parallel, states and corporations consolidated power through neoliberal applications of evidence. Following a concerted campaign in the 1970s by the Mont Pelerin Society to build a network of allies in treasuries, boardrooms, and academic departments, neoclassical economic theorems were exalted by elites as credible evidence that "stagnant" markets needed freedom from restrictive rules and that "inefficient" governments should outsource essential functions to private firms (Mirowski and Plehwe, 2015). This theoretical design for the reorganization of international capitalism was wedded to the political project of seizing power for economic elites, as seen in the way Chicago Boy advisors shoehorned this evidence into state policy across Latin America, worsening poverty and rationalizing authoritarian abuse. Reagan and Thatcher cemented state transitions toward neoliberalism using "powers of persuasion, co-optation, bribery, and threat to maintain the climate of consent" (Harvey, 2005, p. 40), and by the 1990s, countries worldwide were being integrated into global capital markets, seeing state social services dismantled, and undergoing harsh crackdowns on labor organizing. When low-income countries struggled in this new "dollar-Wall Street" regime (Gowan, 1999), the IMF and World Bank insisted that their evidence supported use of structural adjustment programs to eviscerate welfare aid.

By the 2020s, a "Silicon Valley" notion of evidence had come of age. Rooted in an amalgamation of old and new philosophies including transhumanism, cosmism, effective altruism, and long-termism, among others (Torres, 2023), Silicon Valley evidence was built less on the authority of history ("historical evidence") than on speculative visions of the *future*. STS scholars have studied the ways in which socio-technical imaginaries and promissory futures are generated and exert socio-political and material influences (Jasanoff and Kim, 2015; Konrad et al., 2017). However, today these imaginaries are being treated as if they *are* S&T evidence. The (antiquated) past is seen as irrelevant; only the (innovative) future matters. Such visions help mobilize and funnel large flows of capital from venture funds and foundations into research and development, with the goal of realizing these visions. Their evidentiary power is rooted, in part, in the expectation that investors must make money from turning hype into profit, and profit into evidence that innovation goals have been met—regardless of whether those goals match social objectives relevant to people beyond the investor class.

The Silicon Valley figure Marc Andreessen offers a poignant example. Breathlessly extolling the virtues of AI therapists, school tutors, lab assistants, and military advisors, Andressen's Techno-Optimist Manifesto (2023) merges neo-Darwinism with free market fundamentalism to outline a vision of technologists as the authors of a future made bright under a "techno-capital machine." While regarded as unhinged by more sober observers (Bhalla and Robinson, 2023; Lashinsky, 2023), Andressen's worldview is shared by many elites, including Elon Musk, Jeff Bezos, and Sam Altman who represent some of the wealthiest men on the planet and whose norms, whims, and expectations are reshaping much S&T evidence today. The bundle of ideologies they espouse is not homogenous; it contains schisms, for example, over whether AI risks are either negligible or represent existential threats to humanity. Regardless, many Silicon Valley types share a fundamental belief in the power of technology, prioritizing hypothetical anxieties and dreams over the material lives of people today (Doctorow, 2023; White, 2023). Today, these tech titans are using their firms' sizable influence *to create a future into which evidence fits*—"a deeply impoverished utopianism crafted almost entirely by affluent white men at elite universities and in Silicon Valley, who now want to impose this vision on the rest of humanity" (Torres, 2023).

The history of S&T evidence serves at once to contextualize the present moment and to illustrate that "evidence" is not a static concept but rather has evolved alongside the changing character of Global North science, as it first drew epistemic boundaries around colonial "truths," later institutionalized methods of authenticating evidence for postwar nation-building, and still later wedded science to neoliberal globalization and the speculative futures of Silicon Valley financiers. Instead of being anchored only in scientific practice, today's S&T evidence pulls from multiple spheres of expertise and authority, each with particular ways of collecting data, verifying information, authenticating evidence, and building knowledge—in short, shoring up what people believe and why. Yet, evidence is never simply hegemonic: Resistances keep recurring as colonized peoples, disadvantaged communities, and subaltern scientists push back against what the evidence ostensibly says, or produce their own.

4. Methods

We surveyed a wide array of published materials on climate change and gene editing in agriculture, including popular media articles, policy documents, and peer-reviewed science literature. Our objective was to gain an understanding of the broad landscape of initiatives using agricultural gene editing to address climate change. In this initial pass, we identified a variety of laboratories, university-based projects, start-up companies, and public-private partnerships engaged in this work.

For in-depth analysis, we selected the HPI at the Salk Institute due to its substantial funding; its large collection of public facing materials and academic articles; and its rapid emergence as a major node of R&D at the intersection of geoengineering and agricultural gene editing. To build our case study, we canvassed all the public HPI materials we could locate, including its own publications (website pages, brochures, invited talks [e.g., TED and Breakthrough Prize], peer review articles, and conference videos), as well as materials *about* the initiative (popular media coverage, scientific papers, blogs, NGO reports, and an investor presentation). We also conducted a search for U.S. patents that the Salk Institute has filed for in connection with HPI's research.

Using a critical discourse analysis approach (Fairclough, 2013), we then coded these materials to identify salient characteristics of HPI's evidence. We used a combination of descriptive, in vivo, and process coding, allowing us to later derive themes relevant to our review of the history and practice of S&T evidence (Saldaña, 2021). We conducted our coding analysis independently from one another, and then met to commensurate and streamline our codes. After a second pass using the revised codes, we organized our codes into the following categories:

- *Source*: Who is generating the evidence? Is it principally scientists, policymakers, journalists, farmers, citizen activists, NGOs, or communities? When scientists are sources, are they relying on their own scientific research, that of other scientists, and/or other types of information?
- *Type*: What sort of evidence is it? Evidence can be institutional, scientific and technical, practical, experiential, land-based, policy-analytical, market-based, or financial. Scientific and technical evidence itself derives from different disciplines and can comprise qualitative or quantitative data, visual representations, text-based publications, among others.
- *Audience*: Who is the evidence for? S&T evidence is always the selective gathering of information to make appeals to particular audiences; these may include fellow scientists, Indigenous communities, policymakers, environmental caretakers, funders, peasants and farmers, workers, businesses, and the public.
- *Work*: What is evidence doing? Evidence may serve a range of purposes: It may establish a scientific claim, create a framing, reinforce arguments, or be invoked to recruit political and financial supporters.
- *Circulation*: How is evidence moving around? In much contemporary S&T research and development, the media plays a central role in interpreting and translating evidence between different communities (e.g., scientists and publics). For farmers and communities, peer-to-peer interactions are central to their learning.

We ultimately chose to organize our analysis according to "types" of evidence because this allows us to look across, and contrast, the extensive evidence being produced by and around HPI more precisely. This enabled us to delineate 3 main types of evidence used to support HPI's claims: institutional and human evidence; scientific and technical (including environmental and plant molecular biological) evidence; and financial/economic evidence.

To inform our analysis, we also searched for scientific review articles focused on agricultural soil carbon sequestration and consulted via email with several experts in soil science and soil ecology to triangulate our assessment. In the following section, we first provide a background of the Salk Institute and the HPI before sketching the evidentiary claims we have identified.

5. The Salk Institute and its Harnessing Plants Initiative

Founded by Jonathan Salk in 1963, and perched on cliffs overlooking the Pacific Ocean, the Salk Institute in La Jolla, California, is considered one of the world's leading biological science research centers. An independent nonprofit, it cultivates an image of being high-powered while also small, intimate, and mission driven: "unlocking the secrets of life itself is the driving force behind the Salk Institute" (Salk Institute, 2024a). In 2017, several Salk scientists cofounded the Harnessing Plants Initiative, which aims to develop genetically engineered plants that can capture and store carbon. For HPI, climate change is the moral imperative that underwrites the urgency of this endeavor. "Too much atmospheric carbon is raising temperatures around the globe, generating deadly storms, catastrophic flooding and persistent droughts. This is not a problem for future generations to solve. We must address it now" (Salk Institute, 2024b).

The solution hiding in plain sight, according to Salk scientists, is evidence offered by plants themselves. "Today, it is estimated that plants continue to hold as much as 450 gigatons of carbon—*literally living proof* that they provide the most robust and efficient carbon pulldown solution on the planet" (Busch and Miller, 2022, p. 13, emphasis added). The scientists suggest that past and ongoing efforts in the plant research and plant breeding communities across the globe have equipped them with the tools needed to achieve this goal.

To this end, they have trained their efforts on 3 key, and interrelated, interventions. The first focuses on engineering plants with deeper, more extensive root systems. Plants use their root systems to explore surrounding soils for nutrients and water, and several characteristics have the potential, say HPI scientists, to enhance carbon accumulation and stability. Increasing root biomass (number and thickness) could increase overall carbon inputs into the soil. Enhancing root length is also a goal, since microbes do not degrade deep roots as quickly as those closer to the soil surface.

The second HPI intervention aims to boost the sequestration potential of these root systems with a carbon-rich polymer called suberin. Naturally found in the cork oak tree, avocado skins, and many plant roots, suberin absorbs carbon, and at least according to some studies, can be an important component of stable soil carbon. HPI researchers hope that by increasing roots' suberin production, they can harness this molecule's properties, "buying time for civilization to shift away from fossil fuels" (Kaplan, 2021). The third intervention involves the transfer of root growth and suberin traits initially developed in model plants to agricultural crops. Nine crops were initially on the shortlist including corn, soybean, rice, wheat, sorghum and canola (commodity crops grown in large quantities globally) and radish, crimson clover, and annual rye grass (cover crops often rotated with these commodity crops). A paramount goal here, say Salk scientists, is to select genes that confer deep rooting and high root mass without sacrificing crop yield, which they aim to do through genetic screening to identify and control these genes in model species and select crops.

If all goes to plan, the result would not only be "improved" plants but Salk Ideal Plants™ (Salk Institute, 2019a). By 2024, the scientists hoped to have prototypes to begin testing across a range of real-world topographies, climates, soils, and other relevant environmental conditions incorporating feedback into ongoing development and working with industry partners to deploy the plants to farms worldwide. By 2030, they said, their plants would be in widespread use.

A viable strategy? Perhaps. Certainly, it is aspirational. In one journalist's words: "It's an extremely ambitious idea full of so many unknowns—how to get global buy-in from farmers, how many years will it take for plants to reach maturity and will it then be too late, how will mother nature react to such genetic modification and how will these crops taste—that none of Salk's brains have the answers to." Yet it is precisely Salk's brain power, individual and collective, that catalyzes what we argue is a process of building legitimacy through strategies to generate and connect multiple kinds of evidence. In support of its efforts, the Salk Institute articulates—or performs—a series of claims which they support with various types of evidence, each appealing to different audiences: fellow scientists, donors and investors, governments, and the larger public. This evidence falls into 3 major areas, which we explore next.

5.1. Human and institutional evidence

5.1.1. Institutional authority

The institutional authority of the Salk Institute has been built over 6 decades, a time during which the institute has become renowned for its work on cancer biology, immune system biology, metabolism and diabetes, and neuroscience, and plant molecular biology, as well as being celebrated for its Louis Kahn architecture. Multiple Nobel Prize winners and U.S. National Academy of Science members belong to its faculty, and former fellows include Leo Szilard, Francis Crick, and Salvador Luria, among others. In 2004, the *Times Higher Education Supplement* ranked Salk as the world's top biomedicine research institute. The legacy of Salk himself is frequently invoked, as on HPI's website, which says: "Salk's HPI team is embracing the same determination that helped Jonas Salk develop the first polio vaccine and later create the Salk Institute to address other pressing problems for humanity" (Salk Institute, 2024c). Precisely because HPI scientists are *Salk* scientists, their individual expertise is bound up in institutional authority; their statements carry more weight and travel in areas well beyond the natural science realm, including in climate policy and agriculture. The "illustrious past" in which the Salk Institute is embedded (Latour and Woolgar, 1979) serves to guild its "bold futures" in the aura of Western scientific authority, and thus to legitimize "groundbreaking the present" to make those futures manifest.

5.1.2. Individual expertise and authority

The scientists within the HPI are globally leading experts in plant genetics and biology. Their biographies—especially those of Joanne Chory and Wolfgang Busch—are heavily featured on the website (Salk Institute, 2024d), in media coverage, and in talks. In a key brochure, the team is pictured beneath the large heading: "OUR PEOPLE: The top plant biology team in the world" (Salk Institute, 2019a, p. 6). This prestigious status, the brochure explains, builds upon nothing less than the recent revolution in genomics and genetic plant biology, alongside 30 years of molecular plant genetics. It represents a body of knowledge production that the HPI team currently represents: "*We now know* the biological mechanisms of how plants grow, and *understand* the biochemical mechanisms of how plants convert CO_2 into recalcitrant carbon-based molecules. The Salk team is at the cutting edge of these advances and has all the sophisticated multidisciplinary *expertise required for success*" (Salk Institute, 2019a, p. 6, emphases added).

One striking way this evidence about Salk expertise has traveled has been through popular media. An emblematic 2021 article in the *Washington Post* illustrates how perceptions of HPI have been filtered through heroic personalities like that of its founding director, Joanne Chory. The article begins with an anecdote:

> *The world was running out of time, and so was Joanne Chory.*
>
> *The 63-year-old biologist was nearing the end of a distinguished career researching how plants grow. Now she'd won the most prestigious honor in her field, the Breakthrough Foundation's life sciences prize, which came with a $3 million check and an opportunity to address inventors and well-heeled donors at a glitzy Silicon Valley awards ceremony in December 2017.*
>
> *The audience expected Chory to reflect on her achievements. Instead, she seized the chance to issue a warning.* (Kaplan, 2021)

The *Post* story describes how Chory, a Lebanese-American woman, rose in the field of plant biology first by focusing on microbes and later on a tiny, little-studied weed called *Arabidopsis*. "The scientific establishment initially was resistant to the findings—and to the dynamic woman who delivered them. Older researchers would question her analyses. Male classmates and colleagues would try to intimidate her with pranks" (Kaplan, 2021). Chory would defy her male colleagues' sneers to go on to become "a plant research superstar" (Kaplan, 2021). She established her own lab at the Salk Institute. She was elected to the National Academy of Sciences. Her work is today widely taught in biology classes and has inspired generations of women and men scholars after her.

Indeed, the reason Chory was "running out of time" is that in 2004 she was diagnosed with Parkinson's disease. Eventually, Chory's personal health story became deeply enmeshed in the climate crisis ("we are all running out of time")—and in 2019, a TED talk delivered by Chory makes the links explicit: "As a mother, I want to leave the world a better place for my children than the one I inherited. . . . But I also have had Parkinsons for the past 15 years, and this gives me a sense of urgency" (Chory, 2019). This story proved irresistible to journalists and, as it turns out, to deep-pocketed donors, as we describe further below.

The power of these media storylines to amplify scientific evidence—becoming evidence in their own right—is both discursive and material. In the late 2010s, the HPI team was still struggling to raise funds for their genetic geoengineering idea. Few studies beyond proof-of-concept existed, and the NSF and U.S. Department of Agriculture (USDA) had both rejected grant proposals. But Chory's TED talk, preceded by a speech for the 2018 Breakthrough Prize, is widely credited by her colleagues as catalytic moments. In the Breakthrough talk, Chory lays out a vision for a new kind of agriculture. She wants to create "ideal plants"—crops like wheat or rice that are bred to store huge amounts of carbon in their roots (Chory, 2018). If enough farmers replant their fields with these engineered species, they could pull as much as 20% of the carbon dioxide emitted by humans out of the atmosphere each year. She shares her conviction that this vision is not only possible—it *has* to be done.

"She used that stage and highlighted not only the work of plant scientists but . . . this idea of fighting climate change with plant genetics. In a way, that set off this sequence of fortunate events that made us successful," Busch told the *Washington Post*. Shortly afterward, Chory's team were encouraged to apply to the TED Audacious Project, a collaboration of foundations and philanthropists seeking to fund solutions to the world's major problems. The program gave Salk $35 million—several orders of magnitude more than the average NSF grant. Many millions have since been granted by companies and foundations. This cascade of events might on one hand appear like everyday science. A nascent idea attracts funding, the idea gets tested, and more funding and legitimacy follow. On the other hand, most university-based projects are supported by institutional grants (Mazzucato, 2013), while in this case most of the support is coming from philanthropy. The scale of support is also significantly larger; in effect, the initiative is a start-up masquerading as an academic institution. These aspects heighten an already problematic top-down feedback loop, wherein evidence of individual, institutional, and legacy expertise fosters scientific credibility, which in turn garners funding and resources, which can support further research, raising questions about the accountability of science to publics and to whom evidence should speak.

5.2. Scientific and technical evidence

The HPI produces and uses S&T evidence to frame the importance of its work while buttressing its technical credibility. This evidence can be grouped into 2 main areas, distinguished by scale and scope, as well as by purpose and audience. First, HPI scientists engage in *environmental appeals*, "cantilevering" out from their own disciplinary expertise to the technical evidence produced by other scientists working in the climate and soil science fields, to project claims about the future benefits of their work. These appeals are built around the project's potential effects on the global carbon cycle, farmland drawdown of carbon emissions, and soil health. Much of this evidence bridges from science to policy, is used to justify policy and practice arguments, and aims at funder, investor, government, and farmer audiences. Second, HPI scientists provide evidence grounded solidly in their *plant and molecular biology* expertise. By showing evidence of technical knowledge and continual progress, they leverage their core research to speak to other scientists, while also persuading key constituencies such as donors, policymakers, and businesses that research quality lends credibility to HPI's claims about the future.

5.2.1. Environmental appeals

5.2.1.1 The global carbon cycle

The carbon mitigation potential of HPI's project is foundational to its legitimacy. In its public-facing materials, the Salk Institute suggests that to understand the power and feasibility of its approach, one only needs to do some simple math based on extant research on Earth's carbon cycle and human-made carbon emissions: "Each year, 746 billion tons (Gt) of CO_2 are captured and 764 Gt of CO_2 are released, resulting in a net excess of 18 Gt. While reducing this number by 50 percent may seem daunting, 9 Gt is only a small fraction of the total CO_2 naturally captured each year . . . . Simply put, if we can even slightly improve the natural ability of plants to do this, we can have a significant global impact" (Salk Institute, 2019a).

5.2.1.2 The farmland extrapolation

The claim above is supported by extrapolating carbon drawdown from the lab to landscape scale, as well as by estimating conversions of farmland acreage. For example, in a 2021 interview with *MOLD* magazine, Busch anticipates that "if much of the agricultural cropland currently devoted to 6 prevalent food crops is given to growing Salk Ideal Plants, we could achieve a 20 to 46% reduction of excess CO_2 every year" (Day, 2021). In another interview, HPI researchers say that they expect the plants to sequester 4–8 gigatons of CO_2 each year by 2035, or between 10% and 20% of humanity's current annual emissions (Kaplan, 2021). Occasionally, the evidence of carbon drawdown is rendered more abstractly, for example, in terms of harnessing just a "small fraction" of the 450 gigatons of carbon that the Earth's plants worldwide sequester (Busch and Miller, 2022, p. 13).

While it is often unclear how various carbon mitigation calculations are made—or what kinds of assumptions they embed—what is more clear is that *scalability* is key. Initially, HPI scientists considered developing plants to grow on marginal lands. But, as Busch explained in a 2020 interview:

> *[W]e realized that it's all about acreage. Focusing on marginal land, we'd have only a small potential to increase its ability to sequester carbon. Plus, every plant species is different in its lifestyle, and if you have to work with the genetics of many different species, it's a lot of effort. Then it became obvious that we should be focusing on crops, because there are only a handful of species that populate a vast area. There's more than 600 million hectares worldwide for the four most prevalent crops.* (Powell, 2020)

The scaling mandate is not only tied to the ease of monoculture agriculture genetics but also to the recognition that these genetic interventions will likely yield only incremental gains in carbon storage (Salk Institute, 2020). Thus, amplifying the incremental scale, over vast acreage, is the only way to have a significant impact. Such scaling, of course, sparks questions: How might this plan entrench monoculture cropping and the industrial agriculture paradigm it supports? If only industrial farmers are targeted for growing ideal plants, will this exacerbate land and income inequities between large-scale and small-scale farmers globally? Will farmers even *want* to grow "ideal" plants instead of their (presumably nonideal) seeds? We will return to these questions below.

For now, taking the science on its own terms, the carbon evidence is already being challenged by some researchers. Gözde Demirer, assistant professor of chemical engineering at Caltech, told the journal *GenBiotechnology* that engineered crops are likely to make a small dent in the balance of carbon emissions (Grinstein, 2022). She points to studies including a 2023 report in *Plant Physiology*, in which researchers calculated that if the entire U.S. maize crop area (34 million hectares) were engineered to accumulate 0.16 tons/hectare of suberin in roots, scientists would be able to capture and store 13 million tons of CO_2 per year. That amounts to a mere 0.3% of annual U.S. CO_2 production (4.1 billion tons) (Bathe et al., 2023).

HPI researchers acknowledge that their figures are estimates only. In 2020, Busch told reporters that they "did a back of the envelope calculation"[6] to determine how much carbon might be stored in 5 major crops (corn, soy, wheat, rice, canola). They took into account published biomass data to estimate shoot versus root mass. They sized up overall plantable acreage, the proportion of target crops that could be converted, how much of the root biomass might be stabilized, and finally, ran the numbers to arrive at approximately 5.5 gigatons of CO_2 per year. Busch concluded, "I have to say, this is just a very rough calculation, but it showed us that if we could make plants better, it would have a global impact" (Powell, 2020).

To be sure, the nature of science is to tack with uncertainty. Many advances begin with back-of-the napkin calculations that become refined as the empirical data support more accurate assessments. Yet, it is remarkable how this uncertainty is often buried in HPI's narratives, whether in peer-reviewed articles, public-facing materials, or quotes to the media. When moments of reflexivity surface, they are therefore all the more instructive. For example, in a multi-author *Plant Cell* review paper, Chory and Busch acknowledge, "Establishing a link between root traits and carbon accumulation and permanence in agricultural soils will require substantial experimental efforts" (Eckardt et al., 2023). The real-world messiness of agriculture, however, remains largely glossed as sideshow rather than as a central and defining feature.

5.2.1.3 Soil health benefits

From its start, HPI has emphasized soil health benefits alongside carbon sequestration, perhaps recognizing that many farmers are currently less interested in carbon offsets than in assuring their soils remain, or become, more fertile. In celebrating the $35 million grant from the Audacious Project in 2019, a Salk press release quoted Chory saying: "If we can optimize plants' natural ability to capture and store carbon we can develop plants that not only have the potential to reduce carbon dioxide in the atmosphere (negative emissions) but that can also help enrich soils and increase crop yields" (Salk Institute, 2019b). In Chory's TED talk, which has now been viewed more than 2.1 million times online, she further explains:

> *So plants that are making more carbon, those soils become enriched in carbon, and carbon-enriched soils actually hold nitrogen, and they hold sulfur, and they hold phosphate—all the minerals that are required for plants to grow and have a great yield. And they also retain water in the soil as well. So the suberin will break up into little particles and give the soil a new texture. And as we show that we can get more carbon in that soil, the soil will get darker, and we're going to measure all of that, and this is going to solve the problem.* (Chory, 2019)

It does not take a soil science degree to see tensions here. The project aims to lock carbon into soils for "hundreds of years" or longer. Yet it aims to regenerate soils for farmers worldwide in the near-term. So the question of suberin stability versus breakdown appears pivotal. Will suberin remain stable? If so, will CO_2 locked up in its waxy tissues be bioavailable to plants? HPI does not appear to engage this tension directly. However, it is seeking experimental data on suberin longevity (see below).

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[6] Busch's full explanation is as follows: We did a back of the envelope calculation. Taking into account published biomass data and the acreage of the planted crops, how much biomass do they yield above ground? Taking into account root to mass fractions, how much of the plant is root and how much is shoot? We ran these numbers on 5 target crops that we think we can deal with: corn, soy, wheat, rice, canola. We considered that at some point in the future, 70% of the target crops could be enhanced for carbon-sequestration traits. Then we asked, what would happen if we could stabilize 30% of the biomass in the root mass? If you run the numbers, you end up with 5.5 gigatons of CO_2 [per year], which is roughly 30% of the annual surplus [anthropogenic emissions] leaked into the atmosphere. I have to say, this is just a very rough calculation, but it showed us that if we could make plants better, it would have a global impact.

Yet soil ecology scientists we spoke with also pointed to broader carbon cycling and soil health concerns: "flow" of carbon is necessary for providing nutrients to plants, especially in organically managed or natural systems (personal communication, November and December 2023). That is, carbon storage is essential, but you also need *turnover* to release nutrients to plants. Recent studies (e.g., Liang et al., 2019) have even shown that increasing microbial biomass by feeding microbes, letting them die, and allowing their necromass to be turned into soil organic matter is one of the best ways to increase stabilized organic carbon. "So what does this suberin do to microorganisms and how does it affect that turnover?" (personal communication, November and December 2023). There is a tension, another researcher told us, between storing carbon and making it *useful* for other soil processes. "Just having more carbon below ground doesn't mean soil health is 'better'."

Still, HPI scientists have other evidentiary narratives they rely upon. One is making claims about historical soil degradation due to agriculture. For example, Busch and Miller (2022) explain that since the "dawn of agricultural efforts," soil carbon has been substantially depleted, including in the "so-called 'US corn belt' and much of Western Europe." Salk Ideal Plants, they suggest, will help reverse this unfortunate situation. "With this restoration effort, we can expect to see significant improvements in soil quality resulting from increased retention of water and nutrients, which will ultimately fuel an increase in crop productivity. Replenishing soil to their natural carbon-rich state thus has benefits that go far beyond our efforts to gain control of climatic change" (Busch and Miller, 2022).

Obscured in this account is historical evidence that soil depletion is never decoupled from social relations of production, as in feudal Europe when farmland fertility precipitously declined as populations grew but landowners' incessant demand for surplus, underwritten by class inequality, prevented peasants from practicing diversified farming (Patel and Moore, 2017). In the 20th century, industrial agriculture has continued to drive depletion of soil organic matter, erosion of topsoil, and a decline in the biodiversity of soil microorganisms which connect roots with soil, recycle nutrients, decompose organic matter, and respond dynamically to changes in the soil ecosystem (Jacoby et al., 2017; Tahat et al., 2020).

To encourage sustainable production in agroecosystems, researchers now know, microbial community, abundance, diversity, activity, and stability all matter, as does the role of soil biota in plant residue mineralization to form nutrients easily absorbed by plants for growth and development. New research is emerging every day about the importance of symbiotic mycorrhizal associations—such as arbuscular mycorrhizal fungi (AMF)—with roots (Guzman et al., 2021). With evidence indicating that the abundance of AMF and other microorganisms is strongly correlated with crop yield, fruit quality, soil water storage, and nutrient cycling (Doran and Zeiss, 2000; Basu et al., 2018; Mooshammer et al., 2022), long-term carbon storage clearly *is* a question of plant health and soil fertility, and thus, social relations of production. This social-ecological complexity is not lost on HPI researchers. Busch and Chory (in Eckardt et al., 2023) write: "Carbon accumulation and persistence are also dependent on soil type, climate parameters, and agricultural practices such as the use of cover crops and no-till farming (Schmidt et al., 2018)."[7] However, this statement is virtually the only mention—across HPI's public-facing materials—of farming practices as a significant influence on soil health, with even this comment featuring a generic farm without any farmers whose knowledge supports "practices." But the scientists do not easily get derailed by omissions, because they have molecular biology expertise that forms the foundation of their evidence-making, and to which we now turn.

5.2.2. Plant molecular biology foundations

Salk researchers realize that they cannot make ambitious claims about redesigning plants without providing technical evidence of their capacity to accomplish significant structural and biochemical changes to living organisms. Like many molecular biologists, they offer this evidence from within the carefully controlled domain of a model species, in this case *Arabidopsis thaliana* (thale cress, from the mustard family). So far, HPI scientists have identified genes that confer deep rooting and high root mass without adversely affecting crop yield, and have used genome-wide association mapping to find not only causal genes in root growth but the specific variation that has driven phenotypic diversity, evolutionarily. Such experiments give HPI researchers confidence that they are finding important carbon capture traits conserved between *Arabidopsis* and crop species such as maize and rice.

In addition to elucidating paths toward deeper, more extensive plant root systems, HPI researchers are amassing technical evidence for enhancing CO_2 sequestration potential through the biochemical makeup of roots. Here, they have looked to existing studies of cork oak trees, which have revealed key enzymes involved in suberin biosynthesis. They have learned, via other studies, that many regulatory genes for these enzymes are conserved in *Arabidopsis*; such genes, they suggest, represent excellent targets for increasing suberin synthesis. They are also building critical knowledge of how suberin is deposited in specialized cell types, like peridem and exodermis, in roots. Efforts to understand how these cells form and what genetic controls turn suberin expression "on" and "off" are therefore critical to amassing a technical evidence base that moves from "basic" science to "improvement." As Busch and Miller (2022) say: "Continuing to build our knowledge of the genetic regulators underlying the development of these specialized cells and their suberization would allow us to produce future plants with improved potential for carbon sequestration."

The assumption that scientific understanding begets the imperative to "improve" plants goes back to the late

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[7] The citation is to a University of California, Davis paper that shows microbial communities can vary in their composition and density in response to long-term use of cover crops or no-till methods. This is a fairly narrow slice of soil health research.

19th century in plant breeding science, when the merger of Darwinian and Mendelian theories spurred the professionalization of a task previously undertaken by farmer experts (Kingsbury, 2011). By the 1960s, seed improvement had become central to the Green Revolution—a geopolitical project in which HYV arrived in villages across the Global South "carrying the authority of science and modernity" (Yapa, 1993, p. 264). Biological improvement through plant breeding also offered a means for white scientists to negotiate racialized subjectivities, as U.S. researchers believed hybrids could "improve" inferior plant races within a larger project of improving the "primitive" agriculture of Indigenous farmers and peasants in Mexico (Eddens, 2019), and later, vast swathes of the non-white world (Eddens, 2024).

Improvement, then, underscores a broader truth about scientific evidence: It does not hatch fully formed within an R&D project—even a cutting-edge technological project—without a history. Much like plants' evolved genetic variance, evidence has a heritage which shapes the pathways and patterns of activity that the makers and users of evidence act within. This heritage has epistemic strengths, epistemic "blank spots" (matters scholars know they do not understand), and epistemic "blind spots" (which keep scholars from seeing patterns in the world they have not yet noticed). HPI lead scientists all came into the project with deep expertise in molecular biology, plant genetics, chemistry, proteomics, and more, which has shaped how they define problems and the solutions they explore (Friesner et al., 2017). Wolfgang Busch, for example, received his PhD in 2008 from the University of Tübingen, where he identified novel key regulatory genes and modules for plant stem cell control via a systems biology approach integrating transcriptome- and genome-scale transcription factor-DNA binding data. In 2017, after some years as a postdoc and research scientist, Busch came to the Salk Institute as an associate professor and is now a core part of HPI's leadership.

According to media accounts, it was Busch, the root expert, who first suggested that plants could be genetically manipulated to put more carbon in their underground parts. Roots' decomposing tissue could be incorporated into soil, rather than being released into the atmosphere. Evidence that plants can be manipulated in this way relies upon a slow accretion of evidence about root systems that Busch's lab has helped to assemble. Much of this evidence has been authenticated in prestigious peer-reviewed journals, speaking directly to other scientists with the authority to attest to it (cf. Latour and Woolgar, 1979). For example, in 2017, Busch's team published research in the *Proceedings of the National Academies of Sciences* (Di Mambro et al., 2017) showing that, in the *Arabidopsis* root, the boundary between dividing and differentiating cells depends on cytokinin, and in particular, how this hormone interacts with another key plant hormone, auxin, to act as a "trigger" in the plant's developmental transition. In 2019, they published further research in *Cell* (Ogura et al., 2019) showing that auxin is a key factor in controlling root system architecture. Simultaneously, HPI put out a public press release underlining the importance of the study: "Finding this molecular switch is important proof that HPI is on the right track" (Salk News, 2023).

The belief that HPI scientists are "on the right track" has motivated the building of a R&D infrastructure designed to rapidly test genetic changes to ascertain whether these actually improve the root structure and suberin composition of crop plants, initially under lab greenhouse conditions. This infrastructure enables the scientists to ask—and potentially answer—the kinds of familiar molecular biology questions they are trained in. For example: What genes will allow the model plant to express the desired phenotypic traits most efficiently? Can crop plants be genetically engineered to grow deeper, more massive roots, and to produce higher levels of suberin in roots, without interfering with key biological functions?

At Salk, it was Joseph Noel who is credited with calling the HPI team's attention to suberin, a carbon-rich compound that forms the main component of cork (Kaplan, 2021). In nature, suberin is found most abundantly in the cork oak tree (*Quercus suber*), from which layers of tissue are harvested to produce "corks" used to seal wine bottles. Suberin features prominently across the plant world, serving as an outer protective barrier analogous to animals' use of proteins (e.g., collagens) and modified sugars (chitin) (Serra and Geldner, 2022). In roots, suberin's hydrophobic nature provides a barrier thought to reduce water loss and limit the invasion of roots by soil pathogens.

In a 2019 profile of HPI's work, featured in *The Guardian*, the reporter described an aura of "optimism" on a tour of the facilities where Dr Noel works on suberin. "He shows me seed-planting robots,[8] which can bang out a day's work in the time it would take a human weeks; state-of-the-art grow rooms capable of simulating almost any environmental condition; greenhouses sitting atop dramatic bluffs" (Popescu, 2019). Noel, a professor and director of UC San Diego's Jack H. Skirball Center for Chemical Biology and Proteomics, is using the simulation chambers to mimic the conditions of particular climatic zones, including quality of light, seasonal changes, cloud cover, and temperatures. Since the model plant, *Arabidopsis*, has been genome sequenced and grows very rapidly—from seed to seed in 6 weeks—his team is using the mustard relative to churn through experiments rapidly. "It's very easy to change the genetics of it on a massive scale," Noel told the reporter (Popescu, 2019). "If we change a particular gene, we can find out if the roots get deeper, do they get more extensive, does the suberin content change."

Two evidentiary elements are worth underlining here: first is that the production of this evidence is hardly resource neutral. Extensive (and expensive) research facilities are being dedicated to research on suberin and other aspects of "ideal plant" production. Making evidence requires specialized experts like Chory, Busch, and Noel, their lab teams, and the salaries it takes to recruit and

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[8] See also Pierre et al. (2022) and Berrigan et al. (2023).

retain them. It takes robots to plant seeds and lab technicians to take care of the plants, prepare media plates, scan images, and oversee the robots. It takes sophisticated growth chambers to simulate, test, and grow ideal plants. Capital-intensive evidence, in turn, requires funding, a topic to which we return below. Second, this semi-automated infrastructure aims at mass evidence production, not only for the sake of climate urgency but to speed up the process of translating model plant plans to "working" crop varieties. Such an infrastructure evokes the U.S. agricultural experiment stations where HYVs of the Green Revolution were initially developed under carefully controlled, high input conditions, and then dispersed worldwide; the environments of agroecosystems globally were expected to conform to the "universal" norms of those research sites (Dawson et al., 2008). The facilities, too, are designed according to the training and perspectives of the scientists—meaning that the resulting evidence is unlikely to challenge or fill in their molecular biology blind spots, including soil ecosystems and farmer practices.

To be sure, HPI scientists have encountered critiques of their claims about suberin from soil scientists at TED conferences and workshops. For instance, Hanna Poffenbarger, an assistant professor at the University of Kentucky, told Busch: "You should really get some soil scientists on board, because the assumption that we can breed for more recalcitrant roots—that may not be valid" (Popkin, 2021). Recently, then, HPI has begun funding Poffenbarger, as well as Asmeret Berhe at UC Merced, to gather evidence on how suberin decomposes and contributes to soil organic matter (Pratt, 2022). Nonetheless, Busch remains optimistic about suberin's potential, suggesting that while researchers are steadily expanding the islands of the "known" in the sea of "unknown," blind spots created through their onto-epistemic heritage pervade the project, a trouble to which we return below.

5.3. Funding and finance

Public funding for academic research in basic plant biology and applied agricultural science dwindled in the United States and other countries in the late 20th century, even as molecular biology research drew substantial resources from biotechnology and agricultural companies (Buttel, 2005). This trend has only accelerated in the past 20 years (Welsh and Glenna, 2006; Clancy et al., 2016). In this context, as noted above, HPI initially struggled to attract substantial support from traditional science funders such as the NSF and USDA. Following Chory's Breakthrough talk in 2017, the Salk Institute pursued a familiar strategy of emulating industry start-ups by crafting visionary pitches to Silicon Valley-inspired philanthropies (Harris, 2023) as well as fossil fuel companies and hedge fund directors. The outcome: plentiful new funding that amounts to over $135 million in donations to date.

The founding gift of $2 million came in June 2018 from Howard Newman, a Salk board member and private equity investor with interests in oil and gas. Another $35 million began arriving in April 2019 from the TED Audacious Project, an initiative with Silicon Valley origins that aims to "select and nurture a group of big, bold solutions to the world's most urgent challenges" (The Audacious Project, 2024).[9] In November 2020, Sempra Energy presented HPI with $2 million to sponsor a project aimed at designing a drought-tolerant, carbon-sequestering sorghum for use in grain production, grazing, or bio-energy feedstocks in Southern California. One of the world's largest energy companies, Sempra owns Southern California Gas Company and San Diego Gas & Electric, among numerous interests.

Also in November 2020, Jeff Bezos personally announced (Palmer, 2020) that his new foundation was awarding $30 million to HPI (then the only academic recipient) as part of a large tranche of donations to NGOs to support work on climate change (Salk News, 2020a). Remarkably short on detail, the Bezos Earth Fund page notes: "By focusing on prevalent crop plants—which can be readily scaled up within the existing agriculture infrastructure—this project aims to mitigate the effects of climate change, develop more resilient plants and improve soil health" (Bezos Earth Fund, 2020). As we explore below, this implies HPI is leveraging both the energy transitions market and industrial agriculture's supply chains to rapidly expand.

Hess Corporation—a small "independent" oil exploration and production firm—is HPI's most generous supporter. The firm portrays itself as committed to producing energy in an environmentally responsible and socially sensitive way. In February 2020, Hess gave $12.5 million to help meet the "greatest scientific challenge of the 21st century" (Salk News, 2020b). This enabled construction of the new greenhouse described above, with 4 climate-controlled bays and 10,000 sq ft of growing space in which plants can be evaluated, selected, and optimized. The following year, Hess donated another $3 million to establish the Hess Chair in Plant Science, now occupied by Wolfgang Busch (Salk News, 2021). When following up with another $50 million announced in April 2023, Hess noted, since 2020, the HPI team "is rapidly scaling discoveries from laboratory to greenhouse to field" (Salk News, 2023). Distributed over 5 years, this latest gift will create a new Hess Center for Plant Science, hire more faculty, and assist with laboratory and research operations. CEO John Hess is quoted in the press release as saying, "We believe this groundbreaking work will implement scientific breakthroughs on a global scale

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[9] The Audacious Project explains why HPI's work will succeed: "The plant biology scientists at the Salk Institute, led by Joanne Chory, are known for making breakthroughs in their fields. Together with Chory, Salk faculty Joseph Noel, Joseph Ecker, Wolfgang Busch, and Julie Law have already made key successes on core elements of this project. They have located single genes that regulate how deeply roots burrow into soil, they've identified a gene that doubles root biomass, and they've demonstrated the ability to increase the amount of suberin in specific root cell types. The creative team has deep, hands-on knowledge of plants, complementary expertise and grit, along with a practical and ambitious work plan." See https://www.audaciousproject.org/grantees/salk-institute-for-biological-studies.

and can make a major contribution toward achieving the world's ambition to reach net zero emissions."

Assuring access to capital thus underwrites the HPI's rapid growth in material infrastructure, personnel, experimental plants, and knowledge. Sizable funding evidences HPI's strengthening stature as a major scientific venture: if it is garnering so many resources, the purse implies to potential donors and investors, governments, and agricultural companies that its plan must be credible. It also facilitates the ongoing production of evidence for the prospects of carbon drawdown that can in turn generate influxes of capital, potentially influence policymakers, and support the formation of carbon offset markets.

6. Discussion

6.1. Practices

Examining 3 main areas of evidence-making in practice—human and institutional evidence; scientific and technical evidence; and funding/financial evidence—reveals evidence as something that connects immaterial elements of the human experience (belief, trust) to material reality (investments, scientific research, crop planting). This evidence transits a variety of different producers and audiences in reinforcing feedback loops of legitimation. HPI researchers are enlisting support, generating credibility, and amassing material resources in a cycle in which lab research produces scientific evidence, evidence spurs activity within multiple sites and sources of authentication—from *PNAS* papers to Guardian profiles to Breakthrough prizes—and the resultant credentialing, funding, storytelling, and partnering not only drive further research, but importantly, become sources of evidence in their own right.

Evidence of *what*, exactly? The answer need not be very clear, either for the makers or audiences of evidence. As STS literature suggests, the important thing is that expectations are created in which future states become not just a promise but an *inevitability* (Konrad et al., 2017). In many cases, expectations appear in the imperative mode, as seen in Chory's Breakthrough talk where her vision isn't merely hypothetical—it *has* to occur. When statements about what *might* happen are transformed into normative requirements about what *should* happen, evidence becomes fuel for a "promise-requirement cycle" (van Lente and Rip, 1998).

We have also seen how despite all the future talk, the past is also an important source of legitimation for actions that may have empirically thin grounds today. Continual reference to the Salk Institute as a bastion of biological expertise (we are *Salk* scientists) works to authenticate the authority of HPI research by association with the venerated legacy of Salk. The prowess of individual scientists, in turn, is routinely lauded, and their stories of struggle and redemption have become irresistible to journalists and funders alike.

The HPI illuminates how evidence was marshaled to appeal to different constituencies whose conceptions/perceptions of evidence were contingent on particular circumstances and also differed from one another. HPI could use back-of-the-envelope calculations as scientific evidence of global carbon mitigation potential, for example, when attracting donors, corporate partners, and legislators who are currently deliberating on agricultural carbon trading schemes. They could emphasize soil health benefits, in turn, when appealing to farmers and agricultural policymakers, underlining benefits for nutrient cycling, soil fertility, and productivity. They could underline peer-reviewed technical findings—showcasing continuous discovery of genetic mechanisms, regulatory controls, and biochemical pathways in model plants like *Arabadopsis*—when speaking to scientific constituencies. These diverse sets of evidential appeals might not "prove" much empirically from the vantage point of carbon sequestration potential, but they create a web of legitimacy to buffer critiques that inevitably emerge and to help restore public, investor, and media trust in science that plant geoengineering research is on the right track.

However, the Salk scientists are facing a formidable challenge they may currently only glimpse. They are actively generating technical evidence and designing plants, with a future agricultural pathway mapped out and a viable technology founded on precise editing. But once HPI science moves from a U.S. lab-based domain to the wider world of rural practice, policy, and society, conditions become orders of magnitude more complex, messy, and unpredictable. In other words, if the epistemic aperture is opened to include many more kinds of expertise and practice—not only molecular biology, plant science, and climate science—many other kinds and interpretations of evidence will emerge. Some of these evidences may reinforce their visions; others may contravene them. Regardless, it will not be the case that a particular future is inevitable, because other pathways and possibilities will come into view.

The production of evidence from social scientists, farmers, practitioners, Indigenous peoples, movements, and rural communities around the planet—if enabled—will likely complicate Salk's vision enormously. How much land, exactly, is needed to meet the sequestration targets? Whose land? Where, exactly? Back of the envelope calculations referenced by HPI scientists tally gigatons of atmospheric carbon rather than hectares of land required in order to sequester it. Will this land coverage primarily target larger-scale industrial farms? Will it require converting peasant and Indigenous territories into ideal plant plantations? Who might be dispossessed or destabilized here? Will they have a say? Extreme vagueness on land use inspires little confidence from agrarian studies scholars and it will likely not impress farmers, especially smallholders with experience in how nebulous settler projects have reconfigured peasant and Indigenous livelihoods, economies, and lifeworlds in the name of saving humanity (Wright, 2005; Liboiron, 2021). Epistemically just evidence will require taking these concerns seriously.

In addition to blind spots around spatial scale, HPI conjures magical thinking around temporal scale. In 2017, it hoped to produce prototype plants within 5 years subject to funding. In 2019, it expected to deliver these prototype plants within another 5 years. Interrupted by the pandemic, HPI said in 2021 it was finishing tests on model plant species and was beginning initial experiments on widely grown crops like soy and wheat. In late 2022, HPI estimated another 3 years before it would have proof-of-concept plants, let alone field-tested crops (Eckardt et al., 2023). Much like the ever-receding horizon of driverless cars (Norton, 2021), the timeline for the project has already slipped from 2022 to 2025 as the target date for prototype plants. Yet it intends to scale up worldwide distribution by 2030, with significant carbon reductions by 2035.

A more sober analysis of steps to move plants from lab to working landscapes would factor in at least the following considerations: USDA regulators will need to approve the plants for domestic commercial production. Dozens of countries in Europe, Africa, Latin America, and Asia, all with their own regulatory frameworks, will need to do the same. To cover an extensive land base, seeds will need to be multiplied. Thus, agribusiness and biotech firms must devote supply chains for manufacture and distribution of ideal plant seeds, alongside any inputs envisioned. Intellectual property rights, in turn, must be hammered out so that farmers in all distribution sites, across geographies, are allowed to replant these seeds legally; barring that, farmers will need state or private sector subsidies, or very low-cost/free seeds, in order to make cultivation of ideal plants affordable for the (very) long term. Hundreds of millions of food consumers will need to accede to regulatory approvals and agree to purchase foods with ideal plant ingredients. Millions of farmers and Indigenous communities will need to grow these crops instead of, or in addition to, their traditional seed varieties. Salk Ideal Plants must therefore appeal to, or overcome, cultural preferences, local foodways, and ecological relations in which seeds are attached to community, territory, memory, and place.

The ambitious time frame scientists have set for this project also means little room for unpredictable turns. HPI researchers have underlined, for instance, that yields will not be sacrificed, yet it remains unknown how the balance of belowground and aboveground biomass will be affected under real-world conditions, whether additional biomass will require substantially more external inputs, and what the environmental consequences of this fertilizer regime might be. Soil ecologists we consulted had many questions about moving from model plants to agricultural production. The fact that suberin is quite hydrophobic, for instance, could bring unintended consequences for water flows in soils with large suberin deposits at depth. How might this affect interactions with mineral surfaces that protect organic matter from decomposition in the long term? In addition, while HPI scientists aver that they are "on the right track" by having identified a genetic molecular switch that regulates root depth, these studies were conducted in *Arabidopsis*, a very *small* plant compared to corn or wheat. As one soil ecology researcher told us, "I am much more skeptical they would be able to express the traits they want in a field setting with other species" (personal communications, November and December 2023). Even if they can achieve trait expression in crops, trait stability under rapidly changing environmental conditions remains an issue, as does the vulnerability of plants grown in monoculture to cascading bacterial, insect, and fungal disease outbreaks.

In sum, a thicket of unanswered—and *unasked*—questions bedevils the evidence for plant genetic geoengineering. It suggests an extraordinary (though not unprecedented) effort to launch a global technological transfer of "improved" seeds, requiring attendant technical, market, and political coordination to fall into place at lightning speed. It assumes Global South communities will support rather than question the wisdom of devoting farmlands to uncertain carbon capture while Global North countries continue to pollute. It assumes a near-perfect knowledge of soil ecology, where no unpredicted interaction or unforeseen outcome occurs. HPI attempts to sidestep these unknowns by emphasizing the urgency of climate change, which means HPI bears a *moral* requirement to speed up, scale up, and move prototypes out into working crop varieties planted worldwide within the coming decade. The project continues to proceed, attracting support and publicity with relatively little critical attention to date, becoming more credible for elite networks of scientists, industrialists, philanthropists, and policymakers.

Why can the Salk Institute build momentum for its work, regardless of the questions? Why does its evidence outweigh—for the moment—questions about the material, political, and social consequences of implementation? The rapid lab-to-land extrapolation that HPI foresees underlines that the production of evidence is never neutral; it moves smoothly along gradients of power where already better connected, more prestigious, and better funded actors can secure evidence as part of an ongoing process to make their favored future a reality. The tendency of elites is to reproduce evidence within a narrow band of actors whose knowledge and legitimation works to consolidate the dominant social order. If, by contrast, HPI scientists deepen their practices specifically by moving *across the power gradient* to involve, learn from, and defer to the expertises and authorities of marginalized, colonized, and otherwise systemically impacted groups, then more friction around evidence—and possibilities for justice and accountability—should emerge.

6.2. Political economy

As we have described above, HPI scientists put in substantial effort to perform evidence. From another perspective, evidence is forged within and in response to the exigencies of the surrounding political economy, or global capitalism. This means evidence can sustain an institutional apparatus for R&D that develops deeper extractions of surplus value, offers "fixes" for crises caused by capitalism's growth, and designs technologies of control.

It means that the Salk Institute conducts its research within a political economy whose growth for the past 180 years has depended on massive resource extraction, especially of abundant, cheap, fossil fuel energy (Princen et al., 2015). To date, over \$130 million of funds have originated from donors whose wealth is rooted in the production or use of fossil fuels at large scale. While Hess Corporation directly profits from extracting oil and gas, the Bezos Earth Fund exists because of the vast wealth accumulated by Amazon's energy-intensive empire (including cloud computing, digital streaming, and AI, alongside oil-fueled trucks, planes, and warehouses), and the TED Audacious Fund is dominated by technology and Internet tycoons. Today, as this fossil fuel economy faces a slow but inexorable demise, capital is reorganizing around carbon credits, carbon financing, and various forms of offset markets. Companies like Hess understandably float like moths to the argument that the climate crisis can be managed through engineering plants to remove carbon from the atmosphere. While still selling oil, the prospect of generating more capital through trading in carbon offsets also burnishes their reputation and benefits investors. Donations to science serve as proof they are *trying* to change their business models to be more sustainable and ethical in the meantime.

Carbon credits are a key part of HPI's legitimation strategy. If root biomass can actually drive up the stable organic carbon content of soil, effectively sequestering CO_2 from the atmosphere, farmers can be paid a "carbon offset" price. This so-called "terrestrial carbon" strategy, according to a 2019 study by the National Academies of Sciences, Engineering, and Medicine (NASEM), is one of several negative emissions technologies, or NETs, that have received less attention from researchers than traditional mitigation technologies (NASEM, 2019). In 2020, the Earth Futures Initiative—a nonprofit group led by Ernest Moniz, former U.S. Secretary of Energy—published a major report outlining a 10-year, $11-billion research, development, and demonstration program to bring more carbon dioxide removal (CDR) approaches to "deployment readiness" highlighting genetic engineering of plants as a "frontier area" for terrestrial CDR development (Energy Futures Initiative [EFI], 2020). Today, the HPI home page refers visitors to this report for "more information," implying EFI's own work proves the Salk scientists can eventually offer carbon offsets.

HPI is also entering carbon entrepreneurship in its own right. To distribute Salk Ideal Plants widely and seize opportunities in marketing carbon, in early 2023, HPI scientists cofounded a start-up firm, Cquesta (see https://cquesta.com/). Described by incoming Salk Institute president Gerald Joyce as a potential "unicorn" company (with >$1 billion share capitalization) (Clementson, 2023), the new company has licensed at least 9 Salk technology patents,[10] successfully raised $5 million in seed funds (the lead investor is Hess Corporation), and is now working to develop commercially viable root traits for licensing to seed companies (Thomas, 2023; Morrison, 2024). Cquesta promises to "sequester 1 Megaton of carbon by 2028 and 1 Gigaton by 2032." Its business plan appears to target Corteva and Bayer, among other agrochemical companies, in emphasizing covercress and canola. As part of the brassica family to which *Arabidopsis* belongs, these plants might be easier to modify and match the companies' biofuel crop R&D portfolio. Cquesta is also considering targeting soybean, canola, sorghum, corn, and rice crops in North America and Latin America. For their part, farmers are being told that they will not be charged extra for Cquesta's Salk Ideal seeds; they can obtain carbon credits that Cquesta will forward sell, dividing the income with farmers, the agrochemical company, and itself. Farmers *will not need to make* "*significant systems changes*" (e.g., no-till or cover crops), says Cquesta; they can simply plant the new seeds, make money from carbon, and thereby help to rescue the planet (Thomas, 2023). In other words, cover cropping and other diversification practices that work at the systems level are deemed unnecessary, belying significant evidence in agricultural science of their benefits for soil health (see review in Carlisle, 2016).

Universities have been spinning off private companies for several decades in the neoliberal wave of S&T (Glenna et al., 2007). Of particular interest here is how these relationships not only vie to commercialize public knowledge but also help maintain scientific neutrality, by allowing start-ups like Cquesta to lobby for carbon rules and to advertise carbon credit sales. Meanwhile, the Salk Institute can continue to build its evidentiary claims on the legacy of Jonas Salk—"*Our greatest responsibility is to be good ancestors*"—stamping his words and name prominently across many of its public facing materials. Yet scientists dedicated to being good ancestors have pointed out that divesting from fossil fuels would be a sure route for institutions to combat global climate heating (Stephens et al., 2018; Hestres and Hopkes, 2020). Instead, the Salk Institute has launched a project supported by oil industry actors who are not just causing climate change, but who have also been *lying* about climate change for 50 years (Frumhoff et al., 2015).

Moreover, in October 2023, Chevron declared plans to buy Hess Corporation for $53 billion, giving the former potential access to the latter's nascent oil field near Guyana and U.S. shale oil interests (Chevron Corporation, 2023). If Hess was not quite a household name—one that could feasibly grace the facade of a new "Hess Center for Plant Science" complex on the Salk campus—the same is less true for Chevron. The largest 90 investor-owned and state-owned energy companies are estimated to have emitted 914 billion tonnes of CO_2-equivalent between 1854 and 2010, or 63% of global industrial emissions (Heede, 2013; see also Frumhoff et al., 2015). Chevron, ExxonMobil, BP, and Shell alone have contributed 11.33% of emissions, with Chevron's top-ranking share at 3.52% and 51 billion tonnes. Although it remains to be seen whether affiliation with Chevron harms HPI's credibility (assuming the deal proceeds),[11] worse contradictions have survived public scrutiny.

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[10] In a Google Patents search, we identified multiple patents granted by the U.S. Patents Office, the European Patent Office, and WIPO. The scope of a Busch patent (WO2023164515A2) covers methods and designs for increasing expression of suberin in plant roots, while a Chory patent (EP4146811A1) explicitly includes numerous cells, tissues, and nucleic acid sequences, alongside multiple methods. If Salk and Cquesta are following trends set by university/start-up partnerships so far, Salk will be licensing the technology to Cquesta (perhaps exclusively) and Cquesta, in turn, will be generating the seeds and selling them to farmers with licensed "use rights." Farmers will be incentivized to purchase seeds through carbon credits (not because the seeds are free, or necessarily cheaper; they may even be more expensive). Farmers will have to purchase new seeds year to year, it is safe to assume, or else Cquesta would have no business model. It is possible that Cquesta might partner with a development agency like USAID, with international agencies like CGIAR, or with funders like the Gates Foundation, to temporarily distribute these seeds for free to global south regions and farmers.

[11] As of July 2024, the Hess-Chevron deal faced several major obstacles. Chevron must obtain approval from the U.S. Federal Trade Commission; ExxonMobil is battling Chevron in arbitration over its claim to "right of first refusal" to buy Hess' Guyana assets. Key Hess shareholders are expressing opposition to the takeover.

In allying with agribusiness and oil firms in a way that ignores their own contributions to climate change, soil degradation, and biodiversity loss, the Salk Institute risks further "locking in" the industrial agriculture model responsible for environmental breakdown. Few cases offer clearer evidence of a technological fix whose consequences are hugely risky and unpredictable. The true cost, however, is more difficult to measure. It is the opportunity costs when investments and deployment at scale of capital-intensive technologies effectively sabotages more immediately practicable, much lower cost alternatives, such as agroecology. It is the systematic *distraction* from "root cause" problems: the underlying crisis of fossil fuel-driven racial capitalism and the assumptions of colonial/modernity this economic order embeds.

6.3. The colonial/modern world

Since the 15th century, the modern world has been created and organized by colonial power (Quijano, 2000). To become modern has been to achieve whiteness, development, and civilization according to the standards of a Eurocentric order, which privileges particular languages, values, practices, traditions, and ways of knowing and being in an epistemic and material project of imperial conquest and domination (Fanon, 1961; Said, 1978; Dussel, 2000; Chakrabarty, 2008; Vázquez, 2011; Tuhiwai Smith, 2021). A core ontological premise around which this colonial/modern worldmaking grows is the *severing of relations* and *hierarchical separation* across newly constructed categories. If one understands that indigeneity, as it has been defined by Indigenous people, is fundamentally a way of relating, settler colonialism can be understood as having the specific intent to break relations, to destroy relations (Estes, 2019; Estes and Abdou, 2023). In turn, unequal differentiation creates the possibility of separating subject from object, culture from nature, thinking from being. "At the outset, the 'rational subject' was a particular white propertied European male, while other human beings subsisted somewhere in the shadowy territory between subject and object—susceptible to being enslaved and thus legally transformed into object, or married and thereby de-subjectified, or simply regarded as part of the natural world" (Davies, 2016, p. 4; see also Césaire, 2000 [1955]). As many commenters have observed, this subject/object schism also created the conditions for the objectification of land and nature, and thus, propertization, extraction, and violence over the more-than-human world (Grear, 2011; Tomas, 2011; De la Cadena, 2015; The Red Nation, 2021).

Within the colonial/modern order, it is assumed that: (1) Anglo/EuroAmerican societies and knowledge systems are superior; (2) nature and culture constitute separate spaces; (3) science & technology confer control over, and enable extraction from, objectified nature and people; (4) wealth and "resources" should flow from "South" to "North," while costs and violences move in the opposite direction (Arora and Stirling, 2023). The 3 "waves" of S&T history we sketched earlier in this article unsurprisingly embed these colonial/modern assumptions: from the postwar idea that big science—harnessing the atom, going to space, stamping out polio—could create a peaceful and prosperous world to the 21st century notion that scientists and venture capitalists share a common goal of designing life to fit a vision of how "the world" should be.

6.3.1. Control and superiority

The globalized modern world is underpinned by control and domination of humans and more-than-humans it mythologizes as inferior. In one sense, HPI researchers defy this characterization. "Many people," write Busch and his colleague, "still fail to see the transformative power of the plant kingdom. Sitting so quietly and humbly in the ground, it can be easy to overlook or forget the impact that plants have had and continue to have on our everyday lives" (Busch and Miller, 2022, p. 17). Chory's TED Talk puts it more bluntly: "I've come to appreciate that plants, as amazing machines that they are, whose job has been really to suck up CO_2 and they do it so well because they've been doing it for over 500 million years—and they are really good at it" (Chory, 2019). A type of reverence, even inferiority to nature, is apparent here.

In another sense, however, the colonial/modern imaginary of control could not be more palpable than in a project literally called the "Harnessing" Plants Initiative. Arora and Stirling (2023) describe *instrumental imaginaries of control* as directly implicated in globalizing colonial modernity, serving at once to imagine control over the labor of racialized subjects (initially through colonial enslavement and indenture and later through de-development) and to extract value from low-waged workers in global value chains. In this sense, control is a precondition for a colonial-capitalist world economy that runs on "cheap" labor, bodies, nature, and food (Patel and Moore, 2017), as well as on the cheap nature that winds in and out of colonial fixations, at once the object of neglect, disdain, and extraction (and so, chemical pollution, biodiversity collapse, climate chaos) and fetishes of possession, ownership, and control (precious metals, private property, genetically engineered plants).

Metaphors of control appear most evocatively in machine talk. "By using plants as biological carbon scrubbers, as much as half the human contribution to atmospheric carbon dioxide could be trapped semi-permanently in the soil," said Chory to reporters in 2017 (Fikes, 2017). Similarly, HPI suggests: "By increasing root mass, depth and suberin content, Salk researchers will transform wheat, rice, corn and other crops *into carbon-storing machines*" (Salk Institute, 2024b, emphasis added).[12] Controlling imaginations, in this way, models the future like a well-functioning contraption, where the agendas of a "superiorised subject" are imposed onto the "inferiorised" object that is denied recognition for its own agency (Arora and Stirling, 2023; see also Stirling, 2021).

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[12] HPI says: "Plants have evolved into the perfect carbon capture and storage vehicle, offering a readymade solution." See https://www.salk.edu/harnessing-plants-initiative/faq/. This description curiously juxtaposes biological evolution with mechanical technology.

Plants may be "amazing" and hold "transformative power," as the Salk scientists expressed, but they are nonetheless rendered as *inferior* objects that Salk researchers can and must transform into carbon-storing machines.

That fantasies of control and superiority would seep into plant genetic geoengineering is partly expected, given how colonial/modern imaginations have metastasized into many arenas of technoscientific production (Stirling, 2021). But it also contradicts narratives of humility and reverence for the plant world, calling for keen attention not just to the discursive but to the material purposes to which evidence is put. Control can be seen in the state-of-the-art climate-controlled growth chambers where Dr Noel seeks to mimic conditions of particular climatic zones, including light, temperatures, cloud cover, and seasonal changes. It can be seen in efforts to manipulate, via gene editing, plants' genetic composition, growth architectures, root composition, and roots' resultant interactions with soil microbial worlds. It can be seen in the imagined control that industrial supply chains have in placing engineered seeds in farmers' fields globally, as though HPI will not only take plants from growth chambers into working landscapes but can offer *control itself* as a "bold, scalable solution" (Salk Institute, 2024b). The project envisages that Earth will continue to be terraformed according to colonial capitalist desires (Ghosh, 2021): After centuries of land clearing, crop and animal invasions, and industrialization, Earth will be remade to suit not only the "improved" plants of the Green Revolution but indeed the *ideal* plants of the future.

6.3.2. Universal farms and farmers

The rise of European colonial powers, which Dussel calls "the empires of the center," not only expanded the influence of its scientific academies, but coupled the material interventions of empire with its universalizing knowledge systems (Dussel, 2000). In this sense, subaltern communities confront *universalism* as an assault on the wider webs of more-than-human relations with whom their knowledge is formed and shared. Even as various trends (re)emerge to debate more plural and open-ended sustainability transformations (De la Cadena, 2015; Stirling, 2021), universalism maintains a strong grip on science in the 21st century, as seen in the way HPI frames the stakes of its endeavor:

> *Humanity faces an unprecedented threat caused by climate change and a burgeoning global population. To solve this imminent crisis, atmospheric CO_2 levels must be decreased and agricultural production increased.* (Salk Institute, 2019a)

In this framing, a singular "humanity" is under threat, obscuring the expansion of fossil-fuel capitalism in the long 16th century (Moore, 2017a), ecologically unequal exchanges from South to North that have systematically undercut alternative economic pathways (Ajl, 2021; Hickel et al., 2022), and accumulation of wealth in the hands of elites who systematically undercut policy/regulatory efforts to hem in their power (Oreskes and Conway, 2023).

Universalism is particularly apparent in HPI's renderings of agriculture. In an interview with *The Guardian*, Chory explains, "We can't continue to farm the way we farm any more. It can feed 8 to 10 billion people but 50 years from now, there won't be any good soil left so you're just putting the disaster off" (Popescu, 2019). A singularized world agriculture here is deemed culpable for poor soils and impending disaster, effectively erasing peasant, smallholder, and Indigenous agrarianisms that have contributed very little to the climate crisis, and whose practices *build* soil health. "We" farm badly, this universal story goes, eclipsing the *modernization* of agriculture that built industrial food systems and whose extractive regimes propagate the climate crisis. But these histories appear unimportant or inconvenient for HPI objectives. "In fact," Busch and Miller note, "*since the dawn of agricultural efforts*, we have seen a drastic loss of soil carbon and with this loss, a reduction in overall soil quality" (2022, p. 16, emphasis added).

Universalizing the problem also lends itself to universalizing solutions, visible in one principal objective of HPI: to create a single type of genetic modification—applied to a handful of commodity crops—and to scale-up and deploy this innovation across a "world farm" (McMichael, 2009). As with Green Revolution imaginaries, the vision is not altogether fantastic. To the extent that heterogeneous local landscapes worldwide could be re-engineered via mechanization, irrigation, and chemical inputs to mimic conditions in U.S. land grant university experiment stations (Dawson et al., 2008), universal seeds might function in an homogenized agrarian world. In practice, however, the vision was always grander than reality. Green Revolution landscapes resisted this homogenization, and still to this day, the histories of its "successes" are being rewritten (Patel, 2013; Stone, 2022; Edden, 2024).

To be sure, HPI scientists are not entirely dismissive of real-world heterogeneity. In 2017, a 6-step plan outlined that "field testing and improvements" would be needed after the prototype stage to test Salk Ideal Plants in a range of real-world topographies, climates, soils, and other relevant environmental conditions (Salk Institute, 2019a). In various interviews, scientists mention that getting plants out into working landscapes is where the proverbial rubber hits the road, and both policy and farmer preference questions proliferate. Still, the details on this transnational planting endeavor are astonishingly thin. For one, *farmers* are left out of the conversation almost entirely, and when addressed, are treated in universalizing terms. HPI materials primarily reference farmers in 2 contexts. First, as discussed above, when suggesting that farmers will benefit from regenerated soils, enhanced water and nutrient retention, and thus greater productivity. Second, that farmers could sell carbon credits, creating additional sources of income.

But *who* these farmers are, exactly, is never quite clear. It appears Salk Ideal Plants are intended to replace 6 types of major commodity crops, implying that the envisioned farmers are primarily large-scale industrial growers. The carbon calculations imply they will be located worldwide. Universalizing the farmer thus retains a central feature of the corporate food regime, which organizes production and consumption around transnational flows of finance capital and agri-food commodities. Unsurprisingly, HPI scientists emphasize that they are "talking to many different agribusiness companies" because they will not attain the necessary scale "without partnering with big seed companies and big ag" (Busch, quoted in Powell, 2020). With Cquesta, they are now going a step further, linking CO_2 offset markets to genetic geoengineering, and moving universal carbon credits into circuits of accumulation alongside universalized farmers and universalized seeds. It is, of course, possible for colonial/modern narrators to tell violent stories from a benign perspective: "We utilize existing farming practices with superior plant traits and genetics to ensure a more sustainable, resilient, and profitable future for farmers while contributing to a healthier planet" (Cquesta, 2024).

7. Conclusions: Toward a pluriverse of evidence

In 2018, one of the authors of this article attended a public event at UC Berkeley, where a high-profile proponent of genetic engineering was invited to debate a well-known agroecology scientist. A student in the audience asked the agroecologist: "If, as you say, the evidence for agroecology is so strong, why are we not seeing it everywhere? Why isn't *everyone* doing agroecology?" As we have shown in this article, the answer is that the politics of evidence is at work. Evidence is *performed*—marshaled by actors to build legitimacy across multiple sites of authentication. It is shaped by structures of capitalism in which sources and processes of legitimation are molded. It is a product of modern colonial ontologies enveloping how we think, move, and exist in the world. This explains why S&T ventures like the Salk Institute can garner substantially more money, attention, and infrastructure in a relatively short time than agroecologists have enjoyed over decades. What, then, does this mean for agroecologists going forward? What can agroecologists learn from studying the HPI case?

We found that HPI's activities are a future-making project in which evidence is underwriting a potential pathway for global carbon drawdown. Yet, thus far, this evidence is being produced for and is circulating within relatively narrow but elite circles, far from the worlds that most farmers, rural communities, and other land-based workers inhabit. To date, efforts like the HPI have attracted little scrutiny from agrarian communities because, we suspect, these efforts are well-known only within the spaces of donors, scientists, and agribusiness firms. Like many technologies that come out of U.S. labs and Silicon Valley offices, they seem largely distant and irrelevant to most rural peoples—until they suddenly are not. For example, in 2023, Iowans belatedly became aware that OpenAI, Microsoft, and other technology firms were developing AI systems in their backyards, using farmers' precious water supplies to cool the giant data centers during a time of drought (Young, 2024). At this point in the evolution of gene editing in agriculture, evidence inequity predominates.

Evidence inequity, to paraphrase Fisher and Streinz (2021), is about having power to decide what kind of evidence is generated and in what form or format, how and where it is amassed and used, by whom, for what purpose, and for whose benefit. Evidential practices at once respond to and reproduce a larger political economy of capitalist accumulation and ontology of colonial/modernity that together configure the possibility space of evidence. Power is a matter of controlling this evidentiary space.

Below we suggest a few strategies for countering this evidence inequity. Recognizing our positions in Western scientific institutions, we offer these not in a prescriptive sense but rather as areas of ongoing work and practice. Our personal backgrounds also matter in this regard: One of us is Peruvian Quechua with Andean peasant heritage; the other is white Australian. Despite the normative positions we take, we do not stand outside our hybridized subjectivities formed by these colonially structured lineages and relations. We also note that, for simplicity's sake, we use "agroecologists" as shorthand for a highly heterogeneous community of knowledge makers, enmeshed in varying traditions of modern, traditional, Indigenous, Black, peasant, diasporic, and hybrid "alternative modernities" (Gaonkar, 2001; Méndez et al., 2013; Moore, 2017b).

First, agroecologists can work ***on the prevailing terrain of evidence,*** **specifically to mobilize resources from dominant institutions toward agroecology.** Demonstrating that agroecological practices can, in fact, enhance yield and incomes, agroecologists could ramp up appeals to state and private donors, use those dollars to generate more research, and from this research, create more "proof" that agroecology is practicable, fundable, and legitimate. Simultaneously, agroecologists could point to the often-thin evidence for technologies like terrestrial carbon sequestration via gene editing, which have a mostly hypothetical record of efficacy at this time—and large potential risks alongside a highly uncertain, lengthy implementation trajectory.

Second, agroecologists could ***expand the territory of evidence*** **to include a wider panoply of social and environmental values.** Indeed, this expansion is happening already with evaluative frameworks that account for social equity, diversity and exchange of knowledge, cultural food traditions, democratic governance, and circular economic flows, among others (Dumont et al., 2016; HLPE, 2019; Food and Agriculture Organization [FAO], 2024). This path comprises a strategy of *epistemic justice* (Fricker, 2007) by expanding what evidence is used to measure, who benefits, and what is understood as "success." In principle, these actions might contribute to a transformative politics, especially if they seed the kind of *formación* that challenges capitalism's social and ecological injustice (McCune et al., 2017), and in which it becomes conceivable to pursue a third trajectory that we explore in greater detail.

The third strategy consists of ***reclaiming the ontological foundation for evidence***, **enacting a political struggle for pluriversal transition** (Escobar, 2018; Arora and Stirling, 2020). This practice not only broadens the colonial/modern terrain of evidence-making but recognizes and involves multiple terrains, each constituted by unique ways of being and knowing. In so doing, it moves toward what the Zapatistas call "a world of many worlds"—a coming together of communities across radically disparate ontologies to imagine and build reworlding possibilities (EZLN, 1996).

Agroecologists can expect to hear that such a pluriversal path is utopian, romantic, not realistic. Putting aside for the moment that Andreessen's techno-optimistic manifesto is grounded more in fantasy than reality, agroecologists should be prepared to confront this realpolitik by breaking with conventional premises of the real and the possible. What constitutes "reality" has been forged in a colonial/modern crucible that grants entities separate and unequal existences, thanks to its core logic of separation: subject from object, mind from body, nature from humanity, reason from emotion, facts from values, us from them (Davies, 2016; Arora and Stirling, 2020).

If agroecologists can move away from dualistic ontologies toward *relational ontologies*, they will be on firm ground to confront colonial capitalism and the imaginations they circumscribe. To begin, this practice demands relocating the question of "who makes evidence" to communities around the world who, despite centuries of imperialism and colonialism, have resisted assimilation into modernity. These communities represent the Earth's pluriverse and reorient agroecologists to the "uncommons" (De la Cadena and Blaser, 2018) with whom agroecologists can imagine and build *pluriversal evidentiary terrains.* Since each world in the pluriverse comprises its own meanings and ways of relating between different beings (Arora and Stirling, 2020), it is impossible to neatly characterize the whole. But as a normative antidote to the universal colonial/modern order, the pluriverse invites agroecologists to reconceptualize evidence in non-dualistic terms: what evidence *is* can be seen in the *interaction* of entities, rather than in an objectified form. Who makes evidence includes all agential organisms in the more-than-human world. For whom evidence is generated are no longer only dominant actors/institutions but instead those who chose to organize in this uncommons to struggle for a world of many worlds. In this practice, as De la Cadena and Blaser (2018) describe, heterogeneous worlding's come together "as a political ecology of practices, negotiating their difficult being together in heterogeneity."

Major sources for this pluriversal reorientation already exist. They consist of the relational forms of life present among many peasants, smallholders, landless workers, and Indigenous peoples engaged in territorial struggles against the extractive globalization of industrial agriculture (Nyéléni Forum for Food Sovereignty, 2007; 2015; La Via Campesina [LVC] and GRAIN, 2015; AFSA, 2016; MST, 2024). Social movements such as LVC take agroecology very seriously, since land acquired through struggle is often degraded land whose health has been eroded by centuries of colonial extraction and Green Revolution interventions (Rosset and Martínez-Torres, 2012). Faced with this reality, peasants are finding ways to recover their soils and biodiversity in ways that are not cost-prohibitive as petroleum prices soar. Agroecology, in this way, "offers so much hope" (LVC, 2010) for building a new reality grounded in relations that metabolically link communities to territories (see also Wittman, 2009).

Further sources for this anticolonial/modern reorientation can be found in the scholarly world, where many intellectual currents provide insights into relationality. In the biophysical realm, they include many studies of complex systems, including chaos theory, resilience theory, systems biology, phytobiome research, microbiome studies, and more. In the social sciences, Black Studies, feminist studies, Indigenous studies, STS, environmental justice, "third world" studies, and other disciplines have methodologically trespassed academy/community boundaries and become increasingly porous as they grapple with the "ontological turn." For example, the idea of "development," which animated the postwar period, and during which Vannevar Bush promoted research as a peaceful engine of progress, has come under strong scrutiny. In part due to the emergence of ethnic studies, scholars in the Global North have begun critiquing development orthodoxy not only through the lens of EuroAmerican Marxisms but also through anticolonial and Marxist scholarship from African, Latin American, Arab, and Indigenous traditions that decades ago illuminated the colonial-capitalist project of active underdevelopment backed by imperial power (Mariátegui, 1971; Rodney, 1972; Galeano, 1997 [1971]; Césaire, 2000 [1955]; Cabral, 2016 [1966]).

A third source for agroecologists to draw from in this ontological turn is Earth itself. Not in the sense of a "resource" for extractive evidence-making, but rather in witnessing *as evidence* the interdependencies of the planet, and the living organisms and interactions of biophysical, cultural, and epistemic processes that reproduce life. Here, all agroecologists have much to learn from Indigenous communities for whom anthropocentrism remains abnormal. For example, in the Andean cosmovision, mountain communities understand a social-ecological terrain made-up of 3 intersecting realms:

> *the* runa *(domesticated plants and animals), the* sallka (*wild animals, plants, and crop relatives) and the* auki *(the community of the sacred, including apus, pakarinas, and others). According to Quechua belief, only by achieving balance between the land (Pachamama) and these three* ayllus *can one achieve* sumaq qausay, *or "the good life." These interconnected social-ecological* ayllus *reflect the long Andean history of co-evolution between mountain ecosystems and their Indigenous inhabitants.* (Argumedo and Wong, 2010)

The struggle to make/revive the pluriverse is not for Indigenous people alone, however. Not all resistance movements, especially in the West, are ready to jump out of modern skins they have not yet properly molted. Still, all agroecologists can strive to question modern-colonial assumptions and the access to Indigenous land and life these normalize. They can take steps to actively unlearn binaries of separation, superiority, and universality that shape bodies and worlds. They can fight the making of liberal individual subjectivities whose rights—whether property rights or human rights—have undermined a politics and ethics of interdependence (Losurdo, 2014).

While unlearning, agroecologists can organize to demand the *material* conditions for ontological pluriversality: landback to Indigenous peoples, an end to settler occupations, a halt on extractivisms globally, the rematriation of stolen seeds. They can demand divestment from fossil fuels, militarism, prisons, and police. They can build power with social movements that work across these sectors to organize multipronged, short- and long-term struggles for decolonization. No metaphor in this case (Tuck and Yang, 2012; Cabral, 2016 [1966]), decolonization is subversion of power in the form of an end to imperial domination. It is the freedom for people to develop food systems not in the modern-colonial or industrial sense, but within a framework of liberation that frees communities from monopoly capital and emerges through people's sovereignty over their land. These are preconditions of the pluriversal transition.

In this regard, the Harnessing Plants Project has provided a glimpse into the configurations of evidence that effectively smother ontological pluriverses in the cradle under the cool veneer of modern scientific scrutiny. The colonial/modern world, the capitalist political economy, and the performances of evidence they weave together certainly build a particular kind of legitimacy—as seen in the enthusiasm for "ideal plants." But agroecologists must understand the hierarchical ontologies of these commitments, the differences that marginalized groups live with daily, and the inequities that only privileged groups can afford to overlook. Rather than serve as accomplices in acting as if the entire world is, or should be, as colonial-moderns see it, agroecologists can refuse the violence of this premise. They can reworld evidence within a pluriversal practice of negotiating unity in diversity (Amin, 2011), or as feminists of the Global South often say, "living fearlessly with and within difference."

Data accessibility statement

All data gathered for this research are available in publicly accessible repositories, including Salk Institute resources, popular media articles, a range of scientific, social scientific, and historical literatures, policy reports, and start-up company webpages. A selection of the peer-reviewed articles are not open access, but can be accessed via institutional library servers. We also drew on personal communications with several scientists whose shared quotes and perspectives reflected in the article but whose identities are anonymized by request.

Acknowledgments

We would like to thank two anonymous reviewers who commented on this article, the soil scientists who helped us interpret soil carbon sequestration challenges, and the many authors whose lucid analyses we relied upon to make this project possible.

Funding

The University of California, via research start-up funds; and the U.S. Department of Agriculture's Agricultural Extension Station, via faculty funding.

Competing interests

No competing financial interests exist. The corresponding author (Montenegro de Wit) is an associate editor in the Sustainability Transitions domain at *Elementa: Science of the Anthropocene*, in which this article is published. The other author (Iles) is the editor-in-chief of the Sustainability Transitions domain at *Elementa*. As a result, another editor-in-chief has taken responsibility for the article and a guest editor has handled it throughout the review process.

Author contributions

Contributed to conception and design: MMdW, AI.
Contributed to acquisition of data: MMdW, AI.
Contributed to analysis and interpretation of data: MMdW, AI.
Drafted and/or revised the article: MMdW, AI.
Approved the submitted version for publication: MMdW, AI.

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How to cite this article: Montenegro de Wit, M, Iles, A. 2024. The Evidence Project: Genetic (geo)engineering in a climate-changing world. *Elementa: Science of the Anthropocene* 12(1). DOI: https://doi.org/10.1525/elementa.2024.00005

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Knowledge Domain: Sustainability Transitions

Part of an Elementa Special Feature: Ways of Knowing and Being for Agroecology Transitions; Gene Editing the Food System

Published: September 05, 2024 **Accepted:** July 14, 2024 **Submitted:** January 20, 2024

ELEMENTA
Science of the Anthropocene

Elem Sci Anth is a peer-reviewed open access journal published by University of California Press.

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