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Reimagining cosmologies of pore space for pluriversal carbon removal futures

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Efforts to mitigate climate change increasingly hinge on the potential large-scale deployment of geological CO_2 storage. Central to this "carbon management" strategy is the use of subterranean pore space for permanent sequestration. Rather than characterizing it as a neutral void or *sub terra nullius* awaiting productive use from climate techno-fixes, this article examines pore space as a site of ontological and material contestation, entangled with logics and infrastructures of capitalist accumulation and colonial exploitation. We first highlight how contemporary efforts to secure pore space extend longstanding practices of enclosure and extraction, deepening colonial relations, and environmental injustice under the guise of meeting urgent climate mitigation targets. Then, we show how pore space can resist full incorporation into colonial and capitalist frameworks: how its uncertain ownership regimes and unpredictable geologies create "fractures" in extractivist projects. Finally, we explore pathways toward an *otherwise* pore space, drawing on marginalized cosmologies of the underground, geohumanities, negative commons, and community wealth-building literatures. Rather than treating pore space as an empty container for carbon, it can be reimagined as a site of relational practice and cosmological plurality. In doing so, we argue for expanding the study of pore space beyond geology and engineering to include geographers, anthropologists, and critical social scientists, in pursuit of a form of climate governance that foregrounds repair and possibility in the subterranean.

KEYWORDS
carbon dioxide removal, climate change, community wealth building, cosmologies, Indigenous knowledge, negative commons, net zero

1 Introduction

Critical social scientists have long examined how colonial logics and geopolitics extend not just across the land surface, but beneath it—most visibly in contexts of resource extraction and in the development of underground urban infrastructure (Graham, 2004; Scott, 2008; Bridge, 2013; Günel, 2019). This question holds increasing relevance in relation to the mass deployment of "carbon management" technologies that seek to store carbon dioxide in geological formations. The Intergovernmental Panel on Climate Change (IPCC) estimates that several gigatons of CO_2 will need to be durably sequestered every year if we hope to achieve the temperature targets adopted in the Paris Agreement, and on the current trajectory of technological development the majority of that will be stored in the lithosphere (IPCC, 2018). Thus, subterranean pore space—the voids or empty spaces between particles of sand and sediment—represents a critical resource in any imagined future of climate

stabilization. In this Commentary we are concerned with whether the development of this spatial capability will come to replicate and reproduce—materially and ontologically—colonial logics of resource extraction. Or, alternatively, whether it is possible to imagine pore space differently—not as an emptiness available to hide away the toxic legacies of fossil fuel extraction (thus enabling extraction to continue), but as a capability that can be cared for in a manner consistent with the dismantling of fossil fuel infrastructures, and of the modes of geological exploitation that have enabled those infrastructures in the first place.

From a technical perspective, subterranean pore space is a prime resource for permanent carbon storage, as it holds potentially vacuous space inside geologic formations that, according to models, predict can hold CO_2 in solid and liquid forms for millennia (Aldrich and Koerner, 2011). Abandoned and less-productive oil and gas fields have been scoped as carbon storage sites, due to their proven ability to store fluid and gaseous substances over geologic timescales (Gormally et al., 2018), but the scale of underground CO_2 storage implied by climate stabilization pathways requires opening up much larger (and less well-characterized) subterranean spaces for carbon sequestration (Gidden et al., 2025). Alongside the assessment of underground storage potential, scientists and private companies are piloting the coupling of technologies of direct CO_2 capture with underground injection and monitoring capabilities, envisioning a potential future of geological sequestration at climate-relevant scales.

We argue that current conceptualizations of pore space represent a new frontier of resource exploitation, enclosure, and dispossession, legitimized by the urgency of meeting climate stabilization targets. To resist this trend, we need to challenge the notion of pore space as mere available emptiness. We begin by exploring how pore space has been appropriated by legacy extractive industries that have rendered deathly conditions on marginalized communities. We then draw on the opportunities for thinking cosmologically afforded by multispecies justice, negative commons, and community wealth-building literatures. As legal ownership structures for pore space are under contestation and not yet clearly defined, legal avenues for claims to public or common rights in the underground remain open. Such claims run counter to the dominant neoliberal economic model of governance, which in this instance seeks to further enclose and privatize environmental resources under the banner of "green" development (Fairhead et al., 2012). Yet, they offer an opportunity to reimagine and create the social and legal infrastructures that could govern relations with the underground in an era of precarious climate stabilization. A livelier discussion on the future(s) of pore space requires that we open the debate over its uses beyond the necessary techno-economic assessments provided by geologists and fossil fuel extraction engineers, inviting insights from geographers, anthropologists, the humanities, and beyond.

2 Pore space as an extension of colonial and capitalist logics

A longstanding answer to the question of a landowner's rights in English common law is the Latin maxim: "Cuius est solum, eius est usque ad coelum et ad inferos"—or: Whoever owns the soil, it is theirs up to the heavens and down to the depths of the Earth.

As technological advancements took humanity further into aerial space and the underground, this principle was severely qualified to advance different forms of economic exploitation. In the United States and the United Kingdom, the mineral estates and royalties' system was developed in the 19th century to accommodate the emerging oil and gas industry, creating different possibilities for severing ownership of the land as "surface" from that of underground spaces and resources (Richards et al., 2012). The jurisprudence over pore space developed in this context and was generally driven by the interests of extractive actors. Today, the legal nature of subterranean realms is again up for grabs, this time under the aegis of the imperative to sequester "excess" CO_2 in pore space. National and state legislatures are scrambling to define principles, delineate boundaries and articulate compensatory mechanisms in order to identify the rights and liabilities of actors with title to pore space ownership (Gormally et al., 2018; Roberts, 2024; Lezaun, forthcoming).

The subterranean has been described as a *sub terra nullius* (Melo Zurita, 2020). This grammar echoes the colonial doctrine of discovery, which rendered Indigenous lands *terra nullius*; therefore, grantable to new settlers who could find a "productive use" for these violently acquired natural resources (Morgan, 2013; Bhandar, 2014). Povinelli (2016) utilizes the term "geo-ontopower" to describe the ontological violence of colonialism, rearranging what was considered "life" and "non-life" to make such violent extraction of natural resources possible. The definition of productive use has been extended into pore space through narratives that emphasize its potential for economic profit, such as tax credit claims and carbon credit generation, drawing on the experience of injecting CO_2 underground for the purposes of enhanced oil recovery. In ways similar to the colonial period, private equity firms and multinational conglomerates are racing to purchase rights to pore space ownership and use before nation states articulate regulatory boundaries that could complicate their plans (Empower LLC, 2023). By rendering pore space as empty or not intrinsically valuable until "excess" carbon is injected in it is an act of colonial violence, which interprets the subterranean solely as a space of waste disposal and accumulation (Lahiri-Dutt, 2023). This shows how pore space conceptualization acts as an extension of settler-colonial physical appropriation and ontological violence, sacrificing life on the surface and below it in order to build new worlds and negate others (Neimansis, 2023).

As Melo Zurita (2020, p. 5) reminds us, however, "the subterranean is entangled with, not separated from, surface dynamics… Underground projects can displace, expropriate, pollute, and disrupt in the same way that surface projects do." The conceptualization of pore space as a "site of opportunity and contestation" (Gormally et al., 2018, p. 3) represents a new fracturing of space in the interests of legacy actors looking to identify new frontiers of profitable activity compatible with regulatory requirements for emissions reductions. Fossil actors naturally have an advantage in the development of carbon storage, as they can grandfather in decades of landholdings, pipeline and injection well-infrastructure, as well as intellectual property of the geology of the pore space (Jenkins et al., 2023). So far at least, permanent geologic storage has been operationalized by legacy

polluters as a license to continue emitting, contributing to the process not only to further anthropogenic climate change but also to social and environmental harms in proximate communities (Donaghy et al., 2023).

The revolving door between fossil capital and carbon removal has raised alarms among climate activists who see Indigenous land rights and the rights of nature sidelined by capitalist techno-fixes framed as climate solutions (Xiao, 2023; Indigenous Environmental Network, 2021; Malm and Carton, 2021). Carbon removal and storage is not an unlimited resource for balancing unconstrained fossil fuel emissions. Rather, there are limits to how much carbon can be sustainably removed and stored (Smith et al., 2024; Gidden et al., 2025). Grubert and Talati (2024) warn that unregulated carbon markets incentivize the maximization of carbon removals to offset emissions rather than enacting more costly measures to radically reduce those emissions in the first place, thus undermining the notion that geological carbon sequestration will be used just to "balance" or "neutralize" residual or hard-to-abate emissions and to draw down legacy emissions already in the atmosphere. The urgency to ramp up carbon storage in line with technocratic climate model projections lends itself to following the path of least resistance through the marketization of removed and sequestered carbon. The direct application of this technocratic logic risks perpetuating a narrative that frames pore space as a resource for further fossil fuel extraction and securitization, rather than as a collective asset essential for climate stabilization.

3 Toward pluriversal pore space relations

A critical examination of pore space for CO_2 storage fundamentally challenges the inevitability of the continuance of colonial and capitalist relations with the underground. The uneven alignment between natural geological formations and the legibility of property boundaries presents a challenge to the practice of "fracturing" pore space into "bordered volumes" that can be privatized and utilized exclusively. The permeability of the underground between mineral deposits, pore space, and water resources further complicates the relationship between private and common property rights. As Righetti (2017) asserts, "reservoirs operate holistically" without regard to private property or geopolitical boundaries. Geologists can attempt to map the pathway of a carbon dioxide plume when injected underground, but over time the pore space reservoir will diffuse any injected material to stabilize pressure, leading to material trespass and unknown environmental safety consequences for those on the surface (Righetti, 2017).

In practice, this reflects a hybrid property regime with multiple overlapping rights and claims to the land and its resources, where full enclosure and exclusive use is constrained by alternate regimes of governance, such as environmental regulations (Cole and Ostrom, 2012). Existing subsurface intrusions from oil and gas extraction and wastewater disposal raise concerns about how new CO_2 injections will impact energy access, water quality, and possible CO_2 leakage (Righetti, 2017). Can this be the foundation for future pore space relations?

Pluriversal relations in this context imply that communities should be able to self-determine their relations with pore space outside of colonial and capitalist paradigms. This is not just an opportunity, but a necessity to mitigate harm and begin the work of repair (Escobar, 2017). We thus decided to organize this section by exploring three ways of being in relation with pore space outside of extraction: (1) estrangement and healing above ground, rooted in cosmologies of reverence for the underground; (2) community wealth-building, which responds to neoliberalism by redirecting capital flows into marginalized contexts; and (3) the notion of dismantling a "negative commons," which would position geological CO_2 storage more firmly within an effort to dismantle the infrastructures of fossil capital. These ways of being in relation are not fit for every context, nor are they inherently incompatible. Through this section, we intend to invite and uplift thinking that can support communities as they shape their own relations with pore space.

3.1 Estrangement and healing aboveground

Western imaginaries have come to know pore space through the oil and gas industry and technoscientific experimentation and modeling (Neimanis, 2023). What does it look like to imagine pore space relations outside of this paradigm? Fracturing a relationship of extraction may require "estrangement" as Neimanis (2023) suggests, and as Indigenous communities around the world have practiced for time immemorial. Estrangement entails the purposeful physical distancing of human activities from pore space. This protects rock formations deep underground, by supporting the continuance of an uncharismatic ecosystem, populated by a troglofauna and a stygofauna "…composed of crustaceans, beetles, snails, mites, and worms…that have evolved to exist without sunlight, in constant temperatures and are dependent on infiltration of nutrients from the surface world" (Neimanis, 2023, 22). But it also makes way for other forms of knowability of the underground. Rather than being constrained by technocratic Western science, how can the availability of alternative ontologies of the underground complicate what is seemingly unknowable and unimaginable?

These uncharismatic subterranean biomes have been rendered exploitable because they are imagined as existing or potential emptiness, but as Hawkins (2020) urges, "rethinking and re-assembling the underground as a site of life," thoroughly entangled with the surface, provides room for new relationalities. It complements existing Rights of Nature protections, where more-than-human kin are granted standing in legal courts. For example, the Ponca Nation of Oklahoma passed a Rights of Nature resolution in 2017 to protect human and more-than-human kin from further extractive activity, stating that:

"We as Poncas see increased rates of death in our community which have no explanation other than the severe alteration of Nature caused by human technology, science, and the unthinking, unmanaged and unfettered use of oil, gas and coal… Attaining

freedom will require all humans to use knowledge to act in collaboration with Nature" (Ponca Tribe of Indians of Oklahoma, 2019, 2).

Attempting to know about the inner workings of pore space from a technocratic perspective necessitates significant disruption of life both underground and overground (Neimanis, 2023). By concentrating on healing and recovery for the overground, estrangement represents a point of departure from paradigms of conservation that assume that biomes can only remain "pure" or "natural" when left without human stewardship. This notion upholds a deeply colonial premise of a radical divide between humans and nature—a premise often used to justify land dispossession in the name of "protection." Estrangement, and healing above ground, is an active means by which humanity can respect the work of the underground.

3.2 Community wealth-building

Globalization, driven by neoliberal economic policies, freed the movement of capital around the world, opening up new forms of enclosure and extraction of value while failing to generate wealth for the majority of local communities (Harvey, 2005). Pore space, in this context, represents a site of capitalist accumulation by dispossession (Ibid). But pore space, like any form of infrastructure, can also serve alimentary and life-giving purposes, as LaDuke and Cowen (2020) offer: "infrastructure is not simply 'matter that moves other matter,' but rather, in its anti-colonial conception, [it can be] life-giving and capable of sustaining not only the body, but the spirit and law as well" (252).

Community wealth building (CWB), coined by The Democracy Collaborative in the mid 2000s, is a progressive international policy agenda for economic system change that offers an alternative to extractive neoliberal economic policies (Hanna and Kelly, 2021; Guinan and O'Neill, 2019). CWB calls for a kind of regenerative economics that would strengthen local economic development and build systems of local democratic control to ensure that resources are reinvested within communities to build and retain wealth locally. Under CWB, local institutions, such as hospitals, universities, credit unions, and local government agencies, work together to restructure supply chains to better support an economic ecosystem that builds and redistributes wealth locally (Lacey-Barnacle and Boucher, 2025). Rather than solely thinking about wealth and extraction as capital accumulation, CWB interrogates a richer opportunity for infusing capital into local communities, which could support the growth of local renewable energy cooperatives, and, conceivably, community-owned and operated carbon dioxide removal and storage projects utilizing locally accessible pore space. But pore space is much more than an economic resource, it is a "critical commons" where the degradation of the space can be influenced by non-local drivers, such as global markets, and have implications across boundaries, beyond the geography of the community (Gormally et al., 2018). And communities are much more than their human inhabitants; they are complex and entangled multispecies ecologies (Tsing, 2013).

To approach the possibility of convivial permanent geologic storage, where everyone can participate, pore space must be governed not simply as an economic resource, but as a transboundary ecological relation (Dietz et al., 2003). Breaking from traditional projects of extraction, the use of pore space through CWB would go hand in hand with the creation of opportunities for new socio-political relations and alternative ways of governing infrastructure—particularly when wielded by politically marginalized communities (Murrey and Mollett, 2023). Extraction does not just occur as the physical removal of a natural resource from a site, but functions as a wholesale reordering of nature into a natural resource, and places and bodies into sacrificial dump sites or surplus labor (Murrey and Mollett, 2023). CWB radically problematizes extraction. Geological carbon sequestration then becomes a site for self-determination, where politically marginalized communities can leverage pore space operations for renewed economic and political power (Curley and Lister, 2020).

3.3 Dismantling a negative commons

A third converging strand of thought would consider the geological storage of CO_2 as part of a larger effort to dismantle and decommission the "negative commons" of fossil modernity. "Negative commons" refers to the "accumulated residues of industrial civilization" (Monnin, 2021), shared realities that we come to share without consent and that, unlike most examples in the literature on commons governance, are defined by the *burdens* they impose on the collective. The entrenched material infrastructures of fossil fuel extraction are a classic case of a negative commons. They represent a constellation of "wastes, ruins, infrastructures, and systemic path dependencies that threaten livability" on our planet (Monnin, 2021).

What could pore space become, then, if not a site for waste disposal? Exploring the affordances of these subterranean spaces for a future of progressive disengagement from fossil modernity necessitates an expanded political imagination. As Monnin (2021) suggests, key to the task of preventing the ruinous persistence of a negative commons is an enduring effort "to constitute publics where none existed, to politicize what was naturalized, and to transform residues into sites of collective inquiry." Turning pore space into a site of collective inquiry implies resisting its privatization, and the forms of epistemic opacity that emerge when a key domain of our planetary existence is transformed into an asset controlled by actors invested in the continued expansion of fossil fuel extraction. Pore space and geological carbon sequestration can only become part of a decommissioning effort if they remain open to public scrutiny and oversight.

In this context, the use of pore space for CO_2 storage can play a critical *memorializing* function. Kyle Powys Whyte's reflections on Time as Kinship resonate particularly strongly here, for climate change requires a diagnosis of when kinship relations between humans and more-than-human kin were severed (Whyte, 2021). Kinship demands reciprocity, trust, transparency, and confidentiality in repairing these relations, and demands

memory of harm and violence. The role of proximate communities is paramount, for geological carbon sequestration needs to always be thought and imagined in relation to those who live aboveground. An ecological practice, and the communities most directly affected by the siting of these new infrastructures must be empowered to act as stewards of their continued presence, even if—or precisely because—that presence is expected to extend for hundreds if not thousands of years.

4 Conclusion

In this Commentary, we have argued that the underground is not predetermined to operate only and always as an economic space; rather, that form of relation is a product of colonial and capitalist modes of being. These modes are not only materially contested but can be ontologically disrupted through pluriversal ways of being in relation with pore space. Estrangement and healing aboveground, community wealth building, and dismantling a negative commons are ways of charting pathways to a world where geological carbon sequestration can be compatible with the dis-assembling of fossil fuel dominance. We call on the still nascent carbon removal industry to depart from the prevailing logic of an extractive relation to the underground. Such a shift is necessary to prevent the reproduction of harm, and to create viable conditions for repair in the territories and communities bearing the brunt of legacy pollution.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AD: Conceptualization, Formal analysis, Funding acquisition, Project administration, Resources, Writing – original draft, Writing – review & editing. DB: Conceptualization, Formal analysis, Funding acquisition, Writing – original draft, Writing – review & editing. JL: Conceptualization, Formal analysis, Funding acquisition, Writing – original draft, Writing – review & editing.

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