Inverting Ecological Infrastructures: How Temporality Structures the Work of Sustainability

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Stephen C. Slota & Elliott Hauser *

Abstract: *»Die Umkehrung ökologischer Infrastrukturen: Wie die Zeitlichkeit Nachhaltigkeitsarbeit strukturiert«.* All conceptions of sustainability presuppose a temporally distributed mode of work, diagnosing past failures to address problems of the future via actions in the present. Sustainability infrastructures necessarily operate along timescales much longer than those that usually inform design and policy work. Since sustainability work demands temporal negotiation, competing visions of sustainability can be distinguished by the ways they relate the past, present, and future to the categories of the human and the natural. Reviewing the history of oyster fishing in the Chesapeake Bay since 1880, we show that infrastructures are sites where sustainability's temporal dissonance is negotiated, terming this *infrastructural articulation work*. These activities are simultaneously supported by sustainability infrastructure and hindered by infrastructures' inherent elusiveness, accretion, and perdurance. We conclude that a deeper understanding of infrastructures and infrastructural articulation work are crucial for the complex negotiation of temporal dissonance that sustainability demands.

Keywords: Critical infrastructure studies, sustainability, temporality, ecological management.

1. Introduction

Sustainability, as an ideal, must inherently negotiate temporal, ontological, and epistemological differences. To be "sustainable," we must characterize the ecological present's trajectory, identify an ecological future, and take actions in the present to realize that future. All of these steps have ontological concerns. What constitutes the ecological present? What is necessary to evaluate an ecological trajectory? What characterizes the ecological future? How can we know the effects of our actions? This paper presents ecological

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information infrastructures as sites that make visible the negotiation of temporality and its associated ontological challenges. Deploying the method of infrastructural inversion (Bowker 1994; Edwards 2010) as a means of recentering our attention to the dynamics of infrastructure, we make visible that which enables knowledge-making and justifies ecological action. This reveals several fruitful similarities between ecology and infrastructures as objects of study.

This paper foregrounds the work demanded by the politico-economic concept of sustainability. We see this work in the history of Chesapeake Bay oyster ecology and policy as articulating and negotiating technologies, behaviors, and policies towards achieving economic, social, and environmental homeostasis. We seek out the varied but often hidden infrastructures across decades that make possible the work of politico-economic sustainability. Doing so shows how the negotiations, conflicts, and outcomes of sustainability work are shaped by the intersections and overlaps of scientific, transportation, political, and economic infrastructures. Our goal is to trace the ecological effects of the physical, knowledge-making, and ecological infrastructures, thereby mutually enriching the fields of infrastructure and sustainability studies within their substantial but under-recognized confluence.

1.1 Contrasting Anthropocene Ecology and Anthropocentric Sustainability

Among the early formulations of ecology was its definition as the relationship between an organism and its environment, the "surrounding exterior world [...] in the broader sense all conditions of existence," accounting for factors both "partly of organic nature, and partly of inorganic nature" (Haeckel 1886, as quoted in Frederichs 1958, 154). More modern formulations of ecology consider communities (Frederichs 1958), politics (Blaike and Brookfield 1987; Greenberg and Park 1994; Forsyth 2004), systems (McCay 1978; Odum 1983), industry (Stahel 1994), and technology (Madge 1993). Ecology as a concept accounts for the broad, overlapping, and mutually constitutive concepts of human activity and the natural world (often as defined by humans, cf. Latour 1987). In this era of the Anthropocene, however, mutual constitution cannot simply imply equivalence. There is a pervasive recognition of the asymmetrical relationship between human and non-human actors and its impact on the climate, biodiversity, and availability of natural resources (Zalasiewicz et al. 2010) which foregrounds the ability of humans to configure and reconfigure the planet as a whole towards our own endeavors. This asymmetry acknowledges the disparate impact humans have on their environments, but also pulls away from a fully anthropocentric character of ecological change. In other words, the emerging ecologies of the

Anthropocene can nonetheless coherently refrain from anthropocentric framings.

The politico-economic concept of sustainability, in contrast, centers both the human and the human endeavor, while relegating ecological processes to the object of management, rather than as active, responsive, and changing dynamics in and of themselves. This centering of the human can be quite literal in some cases. Some renderings of the "three pillars" of sustainability, for instance, depict them as concentric circles, with "economy" and "society" surrounded by "environment" (Purvis, Mao, and Robinson 2019). Even the more common Venn diagram, which centers "sustainability" at the intersection of circles for each pillar, decenters the environment.

Of course, conceptions of sustainability vary between actors, researchers, and instances of application. We argue that sustainability, especially as contrasted with Anthropocene ecology, attempts to manage the non-human by adapting and changing human behaviors, technologies, systems, politics, and organizations. In their study of scholars and researchers in sustainability science, Aminpour et al. (2019) identify four primary "paradigms" of sustainability: 1) a response to the degradation of the environment; 2) common understandings such as the "three pillars" model; 3) "the relationship between population, production, and technology growth and environmental degradation" (2019, 48); and 4) intergenerational equity. Each of these either start from or center the human. Even in its early conceptualization in the 1987 Brundtland report as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (ibid., 16), sustainability is a compromise between human growth and the dynamics of the environment that continues to prioritize human growth and development.

1.2 Centering Work in the Study of Sustainability

From its original instantiation in the 1987 Brundtland report, sustainable development has become a motivating and highly political concept. While the various definitions of sustainability as mentioned in the prior section pervade, the concept of sustainability enfolds layers of meaning as it is operationalized across different contexts. Loconto and Hatanaka (2018) identify how "knowledge politics" characterize sustainability governance, prioritizing certain communities and concepts of expertise as well as instantiating different sets of standards and metrics rooted in a given understanding of what it is to be sustainable. Vea et al. (2020) emphasize the need for defined and understood values necessary for forming boundaries within different and locally specific efforts for ensuring sustainability. This demonstrates both the relative and shifting nature concerning how sustainability is operationalized, as well as how the engagement of human values impacts what sustainability might be in different contexts. Sustainable development is a worldwide priority, but shifting local conditions similarly reconfigure what sustainability might be or mean in different contexts and political environments (Ozili 2022). In this writing, we treat the concepts of "sustainability," "designing for sustainability," and "sustainable development" as roughly interchangeable in their account of the relationship between human and non-human endeavor at a variety of scales.

Centering the work of sustainability leads us to link together and follow scientists, fishermen, policymakers, and even trains through their historical paths. An additional layer of complexity and nuance arises in turn when considering non-human work: ecological systems, populations, and individual organisms also perform homeostasis, or the consistent alignment of resources and temporality across changing landscapes of technology, people, and policy. Planetary-scale feedback loops of the biological world reorganize the physical world that surrounds them, even as physical conditions structure and enfold the natural world, with some arguing that this is a move towards homeostasis in its own right (Lovelock and Margulis 1974). Global processes, independent of human action, might seek homeostasis through mutual constraint, what Deacon (2011) calls *teleodynamic* work. While this recognition is a methodological strength in studies such as this one, it provides an inherent tension for anthropocentric conceptions of sustainability. We are thus unsurprised to discover evidence of these tensions to be widespread, as further addressed within.

1.3 Potentials of Sustainability

The politico-economic core of the notion of sustainability, which decenters the ecology as an object of management rather than an active, changing, potentially homeostatic dynamic, we identify as pervasive, but not inevitable. More nuanced and developed notions of sustainability work could substantially alter its impacts. Sustainability measures might be deployed to better understand aspects of national quality of life (Heal 2012), or in ensuring long-term "safe policy spaces," similarly depending on local context and values (Mouysset et al. 2018). Sustainability might be a driving value in tourism (Nugraheni et al. 2019) or structuring the interspecies relationships between human and animal life (Bergmann 2019). This variability of definition is a virtue. Human understanding of how to live among the non-human world shifts according to human values, ecological and local context, and changing priorities. Sustainability, not just as operationalized in the management of human and non-human spaces but also as a value informing governmental approaches, calls our attention to its locality in terms of measures and priorities, its linkage to the physical and informational worlds of practitioners and policymakers, and its role in underpinning an understanding of how what matters to us might be ensured to exist in the future.

Sustainability is thus framed politically as the capacity to both understand and exert control over the world; infrastructures, both physical and informational, are materializations of that control. Homeostasis, a key goal of sustainable design in this framing, necessitates mediating infrastructures to achieve consistency across temporal scales. As argued by Appel, Anand, and Gupta (2018, 20), "to decenter humans is in part to think about other time spans, the lifetimes of other things that shape life on the planet, and infrastructure is one important element in such a rethinking." The promise of infrastructural control animating both the management of knowledge and in the development of systems is something to be valued even as it is critiqued. The specific infrastructures and kinds of sustainability work studied in this paper could have been otherwise. By tracing their interplay, we seek to assist researchers and policymakers in envisioning and undertaking new kinds of work.

2. Infrastructure: A Medium for Work

Infrastructure studies, and the methodological concept of infrastructural inversion (Bowker 2005; Edwards 2010; Hahn et al. 2018), provide unique leverage for understanding the temporally distributed relationship between human endeavor and the environments in which this endeavor takes place – the broader ecology of work. Infrastructural inversion, originally proposed by Bowker as a description of the strategic approach taken by French oil services company Schlumberger in developing oil fields in the early 20th century, has come to denote the method of foregrounding infrastructures and infrastructural processes in the analysis of systems (Bowker 1994). While this initial formulation, employed by Bowker (1994) here and Edwards (2010) in his study of climate science infrastructure, focuses on how infrastructural inversion is employed by actors in a studied community, infrastructural inversion has become a method in its own right (Karasti, Pipek, and Bowker 2018). Following Slota and Bowker (2017), we consider infrastructural inversion as moving "away from the spectacle of the pageant of history towards the formation and operation of infrastructures," a move similar to that undertaken by Bowker and Star (2000) in their account of classification systems. We consider infrastructural inversion to be the re-centering, over time, of attention to the dynamics, development, and consequence of infrastructure as revelatory of social, material, and even temporal dynamics that, due to the transparent and embedded nature of infrastructure, might otherwise remain unseen.

2.1 What Are Infrastructures?

We define infrastructure as the systems, organizations, standards, processes, and material that underpin or otherwise support work (Slota and Bowker 2017). Attention to infrastructure renders more visible not only *what* is happening, but *how* it is happening. Infrastructural inversion exposes invisible labor (Star and Strauss 1999), reveals politics and power dynamics (Jensen 2008; Pelizza 2016), and can be used to explore the relationship between human and non-human actors (Morita 2017). This section highlights aspects of infrastructure and literature from infrastructure studies most applicable to the study of sustainability practice. We highlight that infrastructure is relational, temporally recursive, and functionally accretive. When designed or when newly constructed, infrastructure functions as the partial realization of an imaginary, an imaginary that is quickly permuted via its very relationality, recursion, and accretion.

Infrastructure is relational (Jewett and Kling 1991) – we see something as infrastructure when it works in an infrastructural role and bears the characteristics of infrastructure. What might be infrastructure for one person's activity is the subject of work (itself supported by its own infrastructure) for another (Star and Ruhleder 1996). For example, the network of pipes, pumps, interconnection standards, and treatment facilities that are the subject of daily work for a plumber and those working on water delivery, is infrastructure to the line cook filling a stock pot for soup. Arising from the notion of relationality, infrastructure is not limited to systems designed as infrastructure, or even technology – even non-human life might be thought of as infrastructural to some forms of work (Barua 2021). This relationality is also temporal. Developing for immediate needs with an eye to the future is a characteristic concern of sustainability work that, much like infrastructure itself, exists in the "long now" (Ribes and Finholt 2009).

Infrastructure is built upon itself (Edwards 2010; Edwards et al. 2013) and prior infrastructures: the Internet was first supported by adjustments to telephone infrastructure, which built upon telegraph lines, which themselves followed roads, canals, and trails. As such, infrastructures can be thought of as temporally as well as systematically accretive, both embodying past infrastructures in their development while oriented towards the future. In parallel to sustainability itself, understood as a degree of homeostasis of the relationship between human and non-human worlds, infrastructure itself is infrastructure when it achieves some level of homeostasis across a similarly changing set of systems that accrete (Anand 2016) together in a messy, uncoordinated fashion.

Infrastructures are partial realizations of some imagined future. Larkin writes that infrastructures are "not just technical objects then but also operate on the level of fantasy and desire. They encode the dreams of individuals and societies and are the vehicles whereby those fantasies are transmitted and made emotionally real" (Larkin 2013, 333). Infrastructure in this mode of enquiry bears a political address – it promises, through the development of technology, a certain future, a dream of the world as subtended by and supported through new infrastructure. In partially realizing this future within the present, it inescapably functions as inertia within the actual future. This is experienced in the present as resistance to the realization of new futures due to the legacies of past imaginaries plus their accretions. The potential responses to this resistance are often failure of the infrastructure project, creating yet another infrastructure project, or the infrastructural articulation work we identify and highlight below.

In this paper, we call attention to the relationship between knowledge infrastructural work and ecological outcomes, as characterized by the pre-computing research on oyster ecologies in the Chesapeake Bay. The knowledge work of ecological science and regulatory policy is materially and immediately entangled with ecological outcomes in the regions, and centering attention on infrastructural dynamics in the mode of infrastructural inversion is required in order for these dynamics to become visible over time and across temporal registers. In our attention to pre-computing knowledge infrastructuring, we highlight the interaction between the material world in constraining and structuring knowledge infrastructure and the role of knowledge infrastructure in defining, interpreting, and applying significance to observations of the non-human, in this case, the local ecology of the Chesapeake Bay region.

2.2 When Are Infrastructures?

Our understanding of both the human and non-human worlds, and the infrastructures that support management of those worlds, is rooted in their temporal rhythms and the temporal registers of work. Jackson et al. (2011) identify four major temporal registers that are brought into alignment in various ways within knowledge work: organizational, phenomenal, infrastructural, and narrative. The organizational register refers to the rhythms of how people work together, formally and informally. The phenomenal register represents the rhythms of environmental occurrence. The infrastructural register accounts for the rhythms arising from negotiation with infrastructure, such as the time needed to clean, refine, and curate data, or the temporality of data itself. Finally, the narrative register encompasses the rhythms of daily life. Each of these registers is substantially complex – for example, the infrastructural register might itself encompass disparate rhythms of data collection, refinement, and curation alongside boundaries of when and where that data might be useful (themselves shifting, occasionally predictably, over time) and the time taken to perform analytic tasks (Slota, Fleischmann, and Greenberg 2022).

Through exploration of these temporal registers, we see the negotiation of different time scales, through infrastructure, as fundamental to knowledge work, especially so in ecological management. It is through the infrastructural register that ecological – and even climatic and geological – time scales in the phenomenal register can be distilled to the shorter time scales of human action and inquiry. Understanding an ecology involves understanding how it changes over time, and to do so at a pace faster than that of ecological change. This is temporal negotiation, and in foregrounding temporality and the nature of this negotiation we can better understand how ecological and sustainability work operate through their own temporal dynamics, those of infrastructure, and those of the non-human world.

Climate, biodiversity, and other measures of the health of an ecology are examined and understood according to their own temporal registers and are then produced when the phenomenal register is brought into alignment with other registers (Jackson et al. 2011). Effectiveness of ecological work and infrastructural work are both evaluated according to how well they achieve some level of homeostasis. In this section, we highlight infrastructure as, inherently, a site of temporal negotiation work. Since sustainability work also inherently requires temporal negotiation, sustainability infrastructures are a promising site for both ecology and infrastructure studies.

In these negotiations, both temporally and through infrastructure at large, the relationship between the material, the informational, and work practice is often at stake. Infrastructure is infrastructure when it supports some form of work, and its material – its standards, systems, and physical substrates – both characterize and constrain how that work happens (Star and Ruhleder 1996). The work of maintaining and articulating infrastructure *is* work, and all too often work that is not directly supported or recognized (Slota and Bowker 2017). Infrastructures are assemblages of technical systems, policies, humans, and organizations (Anand 2016).

Both infrastructure and sustainability work are undertaken in the "long now" (Ribes and Finholt 2009), where a fundamental aspect of that work is in the relationship between the needs of the present and the perceived needs of the future. As infrastructures are central and supportive systems relationally present in all work, understanding how the work of sustainability in striving to achieve some form of homeostasis is actually undertaken requires an understanding of both the impingement and constraint of the various infrastructures supporting that work. However, the work of sustaining homeostasis (or performative closure [Wackers 2004]) in a designed system is rooted in the negotiation of temporality. Work in city management policy, for example, is characterized by the "biodegradability" of data (Olmstead 2021; Slota, Fleischmann, and Greenberg 2022), as populations, policy environments, and policy framings shift over time. Similarly, ecologies are dynamic systems, with shifting boundaries across local and relational contexts. Much of the work of both sustainability and infrastructure development takes place not only in the design of new systems, standards, policies, and measures, but also in the articulation of these accreting systems to local environments, new technologies, and new social configurations (Edwards et al. 2013).

2.3 Infrastructural Articulation Work

In this paper, we emphasize the role of articulation work (Star 1991; Suchmann 1996) as a key aspect concerning how infrastructures are deployed to manage ecologies. This *infrastructural articulation* can be understood as the work of coordinating across the messy and accreting systems of infrastructure as well as in the articulation of *praxis* to the constraints and capabilities of infrastructure. We define infrastructural articulation as the mutual fitting of environments, knowledge, and praxis within the information and material infrastructures relevant to that local context. Policymakers, scholars, and practitioners converse between the human and non-human worlds to produce sustainable ecologies. In so doing, knowledge, infrastructural, and ecological goals are articulated to each other, according to the values and concerns of local context, towards developing sustainable approaches. Success and failure of ecological policy initiatives can be helpfully characterized by a historical analysis of the temporal registers of organizational, ecological, and infrastructural processes. This helps situate humans and human activities, such as science and policymaking, within their ecological context.

In the following sections, we present an infrastructural inversion of the local ecology of the Chesapeake Bay watershed, with a focus on the dynamics of its oyster population. We explore how the ecological work in the region at that time was configured through nascent infrastructures of knowledge in the region and explore how growing and changing material infrastructures become part of the local ecology to be managed and accounted for over time like other ecological processes. In this account, we call attention to two different modes of infrastructural articulation. The first is the recognition of failing oyster beds, which required an articulation of ecology to material infrastructure. Second, the development of knowledge infrastructure was articulated in three distinct arenas: local goals for sustainable oyster production, the needs of policy and regulation, and accounts of ecological and community dynamics. In these two modes, we see first how ecology articulates to infrastructure and then how infrastructure is articulated to political, economic, and social goals for the ecology. Through this, we show how ecology, as directed by both human and non-human dynamics, encounters different temporal registers that find their expression in infrastructures.

3. Infrastructural Articulation Work in Oyster Ecology

In this section, we demonstrate how infrastructures articulate to ecologies, and how ecologies articulate to both physical and information infrastructures. To do this, we present a short narrative of conservation efforts around oyster beds in the Chesapeake Bay region, starting in the mid-1800s, and explore both infrastructural articulation and temporal negotiation in guiding and refining those efforts. For this section, we are attentive to three behaviors characteristic of temporal negotiation: observing, predicting, and acting. Observation makes the past visible to the present and, via associated memory practices (Bowker 2005; Hauser 2021), to potential futures as well. Prediction produces a characterization of the future, in terms of observations of the past, intended to be relevant for guiding present action. Action itself, or praxis, is the shaping of the present, informed by an understanding of the past, towards some imagined or predicted future – in this specific case it refers to the transition of observation, prediction, and other knowledge work into ecologically licensed action. We take the third category, action, to be the most methodologically significant. While many studies of ecology focus on discourse, policy frames conceptions concerning the scope of both ecology and sustainability, while a focus on action, both in building infrastructure itself and in working through infrastructures, enables observation and prediction to be deflated into their effects on action.

Each of these three behaviors is, itself, a negotiation of dissonance across different temporal registers, and infrastructures are a medium through which the historical traces of such negotiation can be read. Infrastructures build on other infrastructures (Edwards 2010 ; Hughes 1993) and given the "inertia of the installed base" characteristic of infrastructure (Star and Ruhleder 1996), infrastructure carries within its standards, substrates, and organizations an account of its own history. We are, however, attentive to the "more-than-human" (Anand, Gupta, and Appel 2018) nature of infrastructure and assert, along with Bowker (2018, 212), that "the power of infrastructural thought lies in understanding the hybrid social and technical natures and histories of such projects." Through this infrastructural narrative centering conservation efforts around oysters in the Chesapeake Bay watershed, we show how physical infrastructural development impinged the ecology of oyster beds in the Chesapeake Bay and explore in turn the articulations of policy, knowledge production, and regulation of the new ecology produced therein.

3.1 Infrastructuring and Ecology

The history of the Chesapeake Bay watershed is presented here as a story of oysters and infrastructure, and not just infrastructure in the singular, but in the multiplicity of its interactions. While initial regulation of the Chesapeake watershed concerned the availability of shipping lanes and the preservation of fishing, it also produced a knowledge infrastructure of people studying and understanding the Bay itself, as well as the larger watershed feeding it. On March 28, 1785, the first agreement regulating access to the Chesapeake Bay was made between Virginia and Maryland (both states bordering the Bay) for fishing, tolls, shipping, and the maintenance and support of water transportation infrastructure such as lighthouses, buoys, and so on (Rowland et al. 1888).

This took place at a time in United States history when the power distribution between the individual states and nation were under significant contestation – in this compact is also an agreement that currency exchanges between the states, and for tolls, be conducted in gold or silver by weight and at the same value. In this convention, Pennsylvania's delegation even wrote a letter to express their concern that the potential of shipping tolls, tariffs, or fees might exceed the cost of investment necessary to make the waterway navigable:

> It is thought reasonable that [...] all articles of produce or merchandise, which may be conveyed to or from either of the said two states [...] shall pass throughout free from all duties or tolls whatsoever, other than such tolls as may be established and be necessary for reimbursing expenses incurred by the State [...] in clearing, or for defraying the expense of preserving the navigation of said rivers. (Rowland et al. 1888, 422)

The Mount Vernon Convention, where the above agreement was made, provides rich insight into the regulation and negotiation of transportation infrastructure prior to the prevalence of roadways, railways, or other land-based transportation. Pennsylvania had an interest in this agreement because the Potomac River, which feeds the Bay, is one of the closest shipping lanes available. Water as transportation infrastructure here is a perspicuous case because, barring canal building, rivers, lakes, oceans, and so on cannot be moved from one place to another: it is simultaneously a negotiation between the states who lay claim to regulatory authority of the water and its attendant resources and the planetary system itself. Decisions made about the waterway affect broad communities, and regulation is responsive to the characteristics of the waterway rather than the other way around.

This is a manifold of infrastructures: the waterway itself serves as both transportation and agricultural infrastructure, bearing consequences on industries such as fishing, farming, shipping, and travel. We also see regulatory agreements negotiated between newly empowered states creating an infrastructure by which those waterways might be navigated (lighthouses, dredging, buoys) and regulated (the Act itself). In the 1800s, we see the beginning of policy, as represented in legal action, reacting to shifts in technologies well on their way to becoming infrastructural. The Mount Vernon Convention was informed by many of the recognized technologies of the day. Navigation technologies, in the form of lighthouses, buoys, and shipping technology, emphasized Pennsylvania's interest in securing access to the waterway as the most efficient means for distant transportation available, which in turn influenced both the content and the character of the negotiations (Rowland et al. 1888). In this way, we see material infrastructure not just impacting local ecology but becoming a part of it. As the infrastructures of shipping, canning, and fishing developed, change to the local ecology was inevitable – ecology and infrastructure change together, over time.

In the 1800s, however, a technological shift occurred, bringing not only infrastructural concerns over waterway regulation to the forefront of negotiation but also those concerning conservation and the protection of natural resources. In particular, the development of dredges in the early 1800s, designed to trawl oyster beds while traveling along the Potomac River, presented an immediate regulatory challenge to both the states of Virginia and Maryland. Dredges were used to mine large reefs of oysters and were quickly made illegal by both states by the 1810s, only to be re-legalized shortly after the end of the American Civil War (Cronin 1986):

> For oysters, the coincidence of the importation of deep-water dredges, development of new technologies, high demand, and the discovery of large unknown beds resulted in a new important industry and changed the ecology of the Bay. The effects of poor management were also discovered. (Cronin 1986, 188)

In addition to improved dredgers, canning technology made it not only feasible but profitable to harvest far more oysters than the local demand entailed. The development of railroad infrastructure expanded potential market size, and the demand for oyster shells also rose, prompting harvesters to break apart the oyster reefs themselves.

Technologies that supported overharvesting, labor issues, and market demand all came together in the late 1800s and early 1900s to significantly deplete the population and viability of the oysters in the Bay, bringing their conservation and regulation to the forefront of watershed management policy (Kennedy and Mountford 2001). During this time, oyster harvests began to drop precipitously, from 14 million bushels in 1874 to 10.6 million bushels in 1879–1880 (Grave 1912). These manifold infrastructures, from transportation to harvesting to economies, both depleted resources in the watershed and paved the way for an increased scope of access to those waterways.

3.2 Observing

In formalizing techniques for observation, the past is used to inform an understanding of the present, and the phenomenal register is brought into alignment with infrastructural and organizational rhythms. Fishing of oysters in the Chesapeake took place before it was well-understood how those oysters propagated and what conditions were required in order for them to thrive. It is in light of the declining population of oysters, understood through economic observations of oysters as a commodity, that local policymakers sought better understanding of the ecology of oyster beds and, in turn, a better understanding of how oysters reproduce. Here we see a key imbrication of both knowledge and material infrastructures into political and economic processes.

Through commissioned reports and the engagement of biologists in the area, knowledge of how to effectively govern the watershed towards the goal of growing oyster populations emerged. In seeking to rehabilitate and support the livelihood of oyster fishers as the oyster beds slowly decreased in yield, policymakers provoked the production of knowledge not only about the state of science and biology relative to the study of oysters, but also a proto-infrastructure through which the knowledge produced by this science could be reflected and incorporated into policy. Asdal and Hobæk (2016) refer to such infrastructures as enabling "assembling work," calling attention to the circulation of paperwork as more than the "silent background" of policy work. This assembling work not only developed the knowledge infrastructure of oyster bed management but also performed significant work in redefining the boundaries of oyster ecology. In doing so, the manifold infrastructures in the region began to enfold each other, coming together in a new "containment" (Schoot and Mather 2021) of infrastructure and oyster health in the region.

While the recommendations of scientists were not fully and immediately adopted into law, there is evidence from later commissions and regulation that the knowledge produced, even in the earliest commissions, was formally acknowledged. This represents a boundary interface between the work of scientists and politicians, where politicians extract some, but not all, of that scientific work as salient to regulatory efforts – an interfacing between different infrastructural modes of ecological observation. This is not "collaboration without consensus," rather it represents different modes of interacting with information infrastructures, where power dynamics become visible in terms of what actions proceed in light of what knowledge can be obtained through that infrastructure.

Policy interest (in the form of requested reports), increased attention from the legislature, and social action (to some extent) produced a scientific interest in the area, with the attendant assessments of oyster population creating both significant interest as well as substantial contestation. A commissioned report recommended the privatization of oyster stock in conjunction with regulating farming and the re-establishment of oyster beds, among other things (Winslow 1882). This report, informed by the advocacy and research of commission member W.K. Brooks, proposed a significantly science-based approach to managing oyster stock, with regular inspections by the Oyster Police, as well as the opening and closing of particular oyster beds as determined by appointed experts in the field.

These recommendations were, by and large, not enacted:

> Despite years of advocacy, Brooks and his successors failed to persuade Maryland legislators to impose effective conservation measures on the state oyster fishery [...] Nor were they able to persuade politicians to encourage the oyster industry to accept intensive scientific management [...]. (Keiner 1998, 284)

The infrastructure of regulation had not yet articulated the knowledge-infrastructures of scientific inquiry – policymakers were concerned not only with the ecology of oyster beds but also the needs of subsistence fishers, the economic interests of the oyster-based industry, and the resources of governance. In short, there was an ontological divide between regulatory policy and knowledge production, enabled by the developing infrastructures supporting observation and monitoring of the oyster beds. In more modern conceptions of sustainability, this ontological divide is still at stake: the "three pillars" of the 1987 Brundtland report account not only for the ecologies of the non-human world but also of human interaction in acknowledging social and economic sustainability alongside environmental.

Conservation was clearly of concern, but also of concern to policymakers was the availability of common land for oyster harvesting, the ability to support local industry, and nascent concerns about empowering the Oyster Police to close and open oyster beds essentially at will. Complete abdication of regulatory power over the watershed and its resources (something negotiated and maintained by the states from the earliest days of the United States) is somewhat different from a "weak role of scientific authority." While conservation was both an issue and a goal of state policymakers, as evidenced by the existence of the commission in the first place, other factors and stakeholders outside of oyster population concerns also influenced the eventual policy outcome:

> There was much hyperbole in [Brooks's] writing but the gist, repeated by commentators then and later, was that political sensitivity to the wishes of oystermen (the result of the desire of politicians to ingratiate themselves with the oystermen for their votes) was contributing to the decline of the oyster industry in Maryland. (Kennedy and Breisch 1983, 160)

Keiner argues that the failure of researchers to achieve their aims "illustrates the weak role of scientific authority in influencing public policy making on a local level" (Keiner 1998, 384). While the states here had a historic policy interest in understanding, supporting, and managing the Chesapeake Bay and its resources, it is clear that policy actions in regard to the regulation of oyster fisheries and the watershed at large were not strictly aligned with contemporary science in the form of solicited research and reports. Brooks's frustration with the process relates to the different interfaces within the information infrastructures supporting observation – it characterizes the fricative relationships between different ontological perspectives enabled by manifold infrastructures operating in the same space.

In terms of monitoring activities, however, researchers were trusted to report accurately about the present state (or immediate near-past state) of oyster populations. Brooks's numbers on the current and declining population of oysters were apparently believed, but his ability to influence future policy, regulation, and management was limited – at least from Brooks's perspective. However, as we will discuss in later sections, regulatory work did begin to articulate the observations and analysis of biologists, Brooks in particular, while also accounting for the knowledge itself that was well on the way to becoming infrastructural to the management of local oyster beds.

3.3 Predicting

Keiner, as above, suspects that the lack of policy action arose from Brooks's inability to accurately predict future yields. However, Keiner's conflation of the lack of policy outcomes drawn directly from scientific recommendations, coupled with the weakness of science's ability to influence the production and enforcement of legislation, fails to account for a core institutionalization of that knowledge – an articulation of policy processes to knowledge infrastructure itself. Prediction is a consistently vital quantity in terms of how policymakers and regulators accept, encode, and respond to scientific recommendations. As it is informed through scientific knowledge production, policy is enabled by the establishment of a manageable, predictable, and bounded subject. Scientific work thus produces a discourse about nature that simultaneously enables scientific work and the work of management in reconfiguring ecologies to center on the human.

Efforts in watershed management about a century after the events discussed in this narrative were closely oriented towards prediction, as both a demonstration of the viability of monitoring efforts as well as a means of assessing and understanding the potential implications of intervention (Slota 2021). In order to address problems with surface water quality (a specific policy goal informed by particular industrial and aquaculture outcomes), policymakers needed not only a means of effective assessment but also predictive knowledge directing intervention efforts. A 2001 report from the

National Academies of Science (NAS) on water quality efforts emphasizes both the aspect of scientific uncertainty and the need for accurate and predictive models in guiding policy and ecological interventions (National Research Council 2001). The models described in the NAS report are predictive models, and the NAS report acknowledges that both scientific uncertainty and the presence of error in their models exist. Ideal model selection, in this report, is in part based on effectively representing uncertainty, in addition to flexibility, low cost, consistency with available data, appropriate complexity, consistency with modern scientific theory, and a focus on the water quality standard (National Research Council 2001).

Model-driven simulations of planet-scale systems are increasingly able to evaluate and predict how localized anthropogenic change propagates throughout the world. Predictive power, while problematized by Keiner (1998) in the regulatory reaction to Brooks's report, is an increasingly weighty factor that determines how regulations are evaluated, selected, and understood. However, data is not consistently useful over time (Olmstead 2021; Slota, Fleischmann, and Greenberg 2022), and changing landscapes of policy, infrastructure, and population can render a given dataset more or less relevant to a given policy question. In prediction, especially prediction reliant on the re-use of data outside of its initial context of collection, there is a necessary articulation between the data that is available, the selection of "problems" as a site of inquiry, and the knowledge needed to direct action therein.

The strength of prediction is closely linked to the quality of data available. Our ability to act in the world, as argued by Jasanoff (2004), is closely linked to what we can know about the world. In predicting, observations of the past are interpolated through the needs and concerns of the present, and the resulting imaginary of the future is then used to guide action in the present. Prediction, though it bears significant authoritative weight in demonstrating scientific understanding of a system, is often burdened with indistinct knowledge claims. Predictive algorithms are frequently tested for their fit to data, predictive models are often judged by how they perform with respect to other models, and neither are consistently retrospectively tested against the actual progress of the events they predict (Harcourt 2007). Prediction can also be a self-fulfilling or self-countering prophecy (cf. studies on predictive policing, such as Kaufmann, Egbert, and Leese 2019, Shapiro 2017, and the reinvention of "accuracy" in drone warfare in Suchman 2020), and knowledge claims arising from prediction tend to be oriented towards demonstrating an understanding of a system or dynamic in the present.

Prediction as temporal negotiation takes place by understanding the past or present through a vision of potential futures, supported and constrained by information infrastructures (cf. Ergen and Suckert 2022, in this issue). This infrastructural dynamic is most immediately visible in the need for accurate, well-curated, and extensive data, but is also present in the selection of available models, in the scope of potential comparison, and in the discursive framing of what is at stake (Slota et al. 2020). An example of this dynamic from another field of ecological importance is in the motivation towards policies addressing climate change (cf. Gengnagel and Zimmermann 2022, in this issue). Climate change is both an evocative example of temporal negotiation as framed by Jackson et al. (2011) in the distilling of the decadal pace of climate change to the rhythms of scientific inquiry, but also presents an example of how prediction works to guide action in the present. Climate change is often characterized and politically motivated by a desire to avoid a predicted state of the world, often far in the future, and measures of climate change are usually evaluated based on where that predicted state might occur (Dessler and Parson 2019).

3.4 Praxis

Despite Brooks's pessimistic view concerning the reception of his work, the knowledge produced by Brooks and other biologists about oysters was acknowledged and incorporated into legislation, which in turn became the basis for regulation:

> While the legislature ignored many of the Oyster Commission's recommendations, it did pass the Cull Law of 1890, which Grave considered to be the most efficient method ever devised for protecting natural oyster beds [...] It also set a minimum legal size of 21 inches for market oysters. Maryland was one of the first states to attempt the enforcement of such a law. (Kennedy and Breisch 1983, 160)

While Keiner emphasizes the Maryland government's unwillingness to totally support Brooks's recommendations (something he himself lamented in his 1891 publication of his report) (Brooks 1891) as signifying the weakness of scientific knowledge production's ability to immediately influence legislation, the passage of the Cull Law, and later the Haman Oyster Law and subsequent Maryland Oyster Survey, as well as the Board of Shell Fish Commission's report, can serve to somewhat redefine that "weakness" as more a product of incremental amelioration than a particular failure of policymakers to recognize scientific knowledge (Grave 1912; Yates 1913). These reports provided a

> tremendous accumulation of information, although incomplete in some aspects of the life history and biology of oysters, [and] was undoubtedly sufficient for arresting the decline in production and for restoring at least some of the former economic strength of the industry, including the oyster packing industry. (Kennedy and Breisch 1983, 161)

In this case, both the transportation infrastructure and the management of oyster populations are characteristic of how regulatory praxis becomes articulated to knowledge infrastructure, and in so doing comes to account for and accommodate new knowledge, technology, and discourses. First, a policy response to a particular problem expands the policy frame to account for and work with a given piece of knowledge or technology, such as regulating first by banning and then legalizing oyster dredgers or by some other means of accounting for the environmental, social, and market changes brought about by railroad and, later, roadway development on the economics of oyster fishing. Then, based on the representations of that knowledge or technology, an understanding of how legislation might be able to provoke change is produced. The knowledge produced by science becomes incorporated into the landscape of that policy – it becomes infrastructural to future regulatory efforts as regulators articulate their understanding of the site to that knowledge. This infrastructure is supported over time through monitoring and observational regimes, and new forms of data collection become accreted to this extant infrastructure.

In the case of the early days of the management of oyster populations in the Chesapeake, this knowledge infrastructure was largely made up of commissioned reports indicating the current state of the population as well as its yields for fishing. This history of reports and legislative action is embodied in knowledge infrastructures supporting further regulation and management. The Oyster Commission report enabled future reports and commissions, and the recommendations that followed over the next several decades began to build into a management regime that looked, from a distance, a lot like what was originally recommended by Brooks, with oyster beds leased for fishing and ongoing monitoring activities as both informing and informed by policy.

Throughout this narrative, physical infrastructure had significant impact on the region, from initial regulation of the watershed related to the negotiation of transport and shipping rights between states immediately following the revolutionary war, to the building of roadways and railroads. Recommendations from scientists supporting the conservation of oyster stock did not account for the values, convictions, and practices of local oyster fishermen and other stakeholders with a vested interest in their availability, management, and regulation. However, the mechanism of the commissioned report as both a monitoring tool and a site for recommendations of legislative action is characteristic of the management of the Chesapeake watershed, with periodic reports, commissions, and subsequent policy adjustments following at a regular pace from the initial Oyster Commission report.

The incorporation of scientific knowledge into the policy process was not a total commitment to a single report, but a process of incremental accretion, adjustment, and action limited by the need to account for stakeholders beyond the subjects of the study and those performing it. In other words, this is an instance of the dynamic of policy articulation to knowledge infrastructure. These mechanisms, over time and with input from participating scientists, closely resemble the dynamic of translation described by Callon in his investigation of the scallop fisheries of St. Brieuc Bay (1984; cf. Collins and Yearley 1992). Callon sees fishermen, scallops, and scientific communities producing a discourse of certainty through the mechanism of translation. Star (1985) notes how citing a work across a disciplinary boundary purged it of its uncertainty, rendering the work more authoritative as a justification for action. This presents a view of apparent scientific certainty as producing political power. In the case of the Chesapeake Bay, scientists speak separately from subsistence and industrial fishermen as well as shippers and transporters, but at least make some claim to represent the oysters themselves.

The process of commissions, reports, and ongoing research translates not only knowledge produced by scientists but also knowledge about scientists in an ongoing, iterative process. Later efforts towards managing the ecology of the Chesapeake Bay watershed took the lifecycle and dynamics of the oyster population, new knowledge at the time of Brooks's Oyster Commission report, as an embedded, assumed fact: a certainty. The regulatory action, as evidenced within the concerns for conservation science and regulatory policy, articulated this new knowledge, which itself became infrastructural to future efforts. Much as the infrastructures themselves accrete over time, so too did the development of knowledge infrastructures supporting the translation of Brooks's and other biologists' work accrete certainty, and license for action, as the ecological work moved across disciplinary boundaries.

Modern regulation focuses much more closely on the management of pollution and water quality through predictive models, as well as provisional boundary figures that enable and support articulation between the ontologies of regulation and scientific inquiry to move together towards defined social goals (Slota 2021). In this way, the modern knowledge infrastructure of ecological management still bears its history, continually maintained across significant changes and the accretion of sensor networks, predictive models, and computation (Slota 2021). This narrative of accretion is not one of inevitable progress but rather illustrates the praxis that infrastructure *sometimes* enables: the slow accumulation of certainty over time that *can*, if properly articulated to some future present, induce action.

4. Discussion

Understanding the world ecologically demands the negotiation of dissonant temporal registers. Climactic time scales must be brought into alignment with the rhythms of data analysis, collaboration, and funding so as to bolster climate science. Regulatory work is then brought into alignment with the rhythms of this scientific inquiry, alongside organizational rhythms necessary for its enforcement. Infrastructure provides a key point of articulation between these registers but is itself subject to temporal coordination and the need for homeostasis in order to continue as infrastructure for this work. Infrastructuring, however, is a slow, messy process of accretion, maintenance, and repair over time. Infrastructure is itself temporally distributed, designed for the "long now" (Ribes and Finholt 2009) but carrying its history in the inertia of the installed base and the nature of infrastructure built primarily upon itself: "a matryoshka of obsolescence and path dependence" (Slota et al. 2020, 13).

4.1 Temporal Registers

Understanding infrastructural articulation helps characterize the various temporal registers commonly negotiated as part of ecological management. An attentiveness to the work of infrastructure can provide leverage for pursuing a homeostasis of natural processes – what fits nicely into the heterogeneous operationalizations of sustainability. Infrastructures do not just occupy material and information spaces – they also occupy organizational, social, and political space, a medium for resonance and dissonance amongst the rhythms active in each.

Given that temporal negotiation is one of the core functions in the work of sustainability, infrastructures accrue properties and characteristics over time. We consider these via the related terms *perdurance* and *accretion*. Perdurance indicates the robustness of infrastructures over time, while accretion describes the specific, almost sedimentary, ways in which they change.

4.2 The Work of Perdurance

The perdurance of infrastructure exceeds the frame of the infrastructure itself. The skills honed in the development and use of infrastructures then attach to later infrastructures. Algorithms (that, for example, "clean" datasets) travel to new projects, importing their particular style of cleanliness. Organizational commitments that were painstakingly negotiated are more easily recreated in the future: the infrastructural articulation work situating infrastructure as the site of temporal negotiation has already taken place. Once it occurs, a kind of articulation work can more easily take place again. Ultimately, the temporal scale of a study of infrastructure is better conceived as decades rather than years – infrastructure is a generational effort and should be studied as such, with close attention paid to the specific forms of articulation work (Star 1991; Suchmann 1996) that supports its homeostasis.

4.3 Attending to Accretion

The principle of infrastructural perdurance does not suggest that infrastructures never change. The specific ways in which they change are important for understanding them, however. Infrastructure provides a throughline, a historical accretion of systems, policies, and ways of knowing, that nevertheless continues to exert influence so long as its substrates and strata perdure. Like particulate matter collecting into sediment, the changes that occur to infrastructures are slow, related to but distinct from the change that occurs through them. Infrastructure functions to enable coordination across temporal registers and scales, and in its material, standards, and politics, significantly restructures the world and life within it.

This conception of change is a helpful addition to the tradition of infrastructure studies. Much of recent scholarship in information- and knowledge-oriented infrastructure studies has been oriented towards the new and the novel, using ways of knowing that are characteristic of modern information and communication technologies. In using historical methods to focus our analysis of infrastructural inversion on the management of oyster ecologies prior to the advent of the Internet, we demonstrate the applicability of infrastructural inversion for other historical sites. This helps reveal infrastructures of sustainability as multi-generational (cf. Yoo et al. 2018) and helps us to envision them as the multi-generational, multi-species collaboration they must become if we are to achieve ecological homeostasis within the Anthropocene.

5. Conclusion

This paper inverts the infrastructures of sustainability within which temporal dissonance and conceptual boundaries between the human and the natural are negotiated, mutually illuminating infrastructure and sustainability studies by reading them through each other.

Original and still-influential conceptions of sustainability construct the human as the negative space left over from the concept of what is natural. In practice, though, the “natural” world is the negative space untouched by human action. The reach of human influence upon planetary ecology is such that the negative space left to “nature” is vanishingly small, and yet “natural” disasters periodically and dissonantly puncture the human world. Similarly, the needs of the present constitute a positive space crowding out the future periodically and dissonantly punctured by the consequences of past actions.

Where might we intervene in these negotiations to tip the balance? We have presented infrastructures as an answer to this question. Our evidence for this answer was drawn from a longitudinal history of a specific watershed, sensitized to its varied infrastructures and the kinds of work they enabled. We traced how the development of economic, transportation, and harvesting infrastructure precipitated a complex crisis in oyster populations, where oysters serve as a key dynamic in the Chesapeake Bay's natural water filtration infrastructure. Articulation between the imagined non-human world and the world as represented through knowledge infrastructure thus becomes fundamentally entwined with the work of sustainability and ecological management.

Infrastructural articulation studies should be more deeply influenced by sustainability studies. Attentiveness to articulation is a recognition that homeostasis represents change over time, not a static state. The specific modes of change over time we identified – perdurance and accretion – cannot be a comprehensive accounting of infrastructural evolution. If, as Jackson, Pompe, and Krieshok (2012) argue, the bulk of infrastructure work is, fundamentally, maintenance and repair, then infrastructure studies has much to learn by studying the work of ecological management. Infrastructure is fundamentally a part of ecology, both for human and non-human behaviors. To disarticulate ecology and infrastructure is to miss significant and consequential dynamics of each. As argued by Barua, "the installation of non-human infrastructures is a quest for managing and governing human life, especially in the face of futures projected as uncertain or turbulent" (2021, 1479).

Temporality is central to the insights in this paper but, as Jackson et al. (2011) point out, it is still underexplored in its implications for organizational and knowledge processes. The infrastructural perspective, when applied to the exploration of temporal negotiation, provides leverage for understanding how work is configured through its temporal dynamics and, in turn, how the shadows of our past, the negative spaces of "the present" or "the natural," are projected into the future. Infrastructure is often *how* those negotiations take place, especially with regard to ecological (phenomenal) temporal registers. In seeking sustainable ecologies, the negotiation of temporal registers highlights the work of sustainability as a multi-generational and adaptive effort.

Sustainability promises stability but demands change, a negotiation between the dissonant needs of the present and those of the future. The default resolution of this dissonance is that the future is left to occupy the negative space of an ever-growing present, just as nature is left to occupy the negative space of the ever-growing human. Alternative resolutions are only possible within spaces that support the work of negotiating the articulation of the future of the non-human within the ever-growing human present. Infrastructures are one such space, situated and resonant with promise, where the negotiations that might constitute an ecology for the Anthropocene can occur.

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