World Development

Unlocking “lock-in” and path dependency: A review across disciplines and socio-environmental contexts

--Manuscript Draft--

Manuscript Number:	WD-20572R3
Article Type:	*Invitation ONLY* Development Review
Keywords:	Lock-in, path dependency, maladaptation, energy, climate change, poverty trap
Corresponding Author:	Benjamin David Neimark, Ph.D. Lancaster University Lancaster, Lancashire UNITED KINGDOM
First Author:	Jenny E Goldstein
Order of Authors:	Jenny E Goldstein
	Benjamin Neimark
	Brian Garvey
	Jacob Phelps
Abstract:	Introduced in the early 2000s, the concept of carbon “lock-in” has been widely adopted by think tanks, academics, and civil society trying to break away from the consequences of fossil-fuel induced carbon emissions and climate change. The concept has been instrumental to energy economic policy, energy transitions, and automobile transportation and urban mobility. It has parallels with “path dependency” across sectors, including water governance, fisheries, farmer tenure, and debt. Yet its use has also fallen short in applying it to nontechnical settings beyond infrastructure. In this review article, we argue that the “lock-in” concept is relevant to a much broader range of multi-scalar socio-environmental challenges to development. We expand lock-in to consider granular issues that tend to slip out of macro-level technological and institutional path dependencies, without falling into the ‘naturalizing trap’ in systems thinking. Broadening and re-engaging the concept of lock-in strengthens our analytical ability to address a range of structurally uneven environmental and societal lock-ins.

Unlocking "lock-in" and path dependency: A review across disciplines and socio-environmental contexts

ABSTRACT:

Introduced in the early 2000s, the concept of carbon "lock-in" has been widely adopted by think tanks, academics, and civil society trying to break away from the consequences of fossil-fuel induced carbon emissions and climate change. The concept has been instrumental to energy economic policy, energy transitions, and automobile transportation and urban mobility. It has parallels with "path dependency" across sectors, including water governance, fisheries, farm tenure, and debt. Yet its use has also fallen short in applying it to nontechnical settings beyond infrastructure. In this review article, we argue that the "lock-in" is conceptually relevant to a much broader range of multi-scalar socio-environmental challenges to development. We expand lock-in to consider granular issues that tend to slip out of macro-level technological and institutional path dependencies, without falling into the 'naturalizing trap' in systems thinking. Broadening and re-engaging the concept of lock-in strengthens our analytical ability to address a range of structurally uneven environmental and societal lock-ins.

Keywords: Lock-in, path dependency, maladaptation, energy, climate change, poverty trap

Highlights

- Lock-in has been widely adopted by policymakers, academics and civil-society groups trying to explain the unique challenges of transitioning away from a fossil fuel-based economy

- Our review of lock-in demonstrates that entrapment is not as simple as infrastructural investments and sub-optimal technological advancements sometimes assumed by the literature
- We argue that assessing how different disciplines analyze lock-in identifies cross-cutting themes and reasons for why, how, and when lock-in emerges
- This review broadens the utility of lock-in and path dependency beyond fossil fuels to understand entrenchment in complex socio-environmental systems

1. INTRODUCTION

In the early 2000s, Gregory Unruh (2000; 2002; 2006) presented the theory of "lock-in" to describe society's ongoing dependencies on fossil fuels and its unique forms of entrenchment involving "interlocking technological, institutional and social forces" (2000, 817). Since then, lock-in has been widely adopted by policymakers, academics, and civil-society groups trying to explain the unique challenges of transitioning away from a fossil fuel-based economy as an empirical phenomenon (e.g., IPCC report, 2007; Seto et al. 2016). This focus is particularly evident in the recent debates on fossil fuels, greenhouse gas emissions, and climate change, and the challenges of infrastructural, transport, and technical lock-in that impede low-carbon energy transitions (Foxon et al., 2005; Bertram et al. 2015; Klitkou et al., 2015). Lock-in as a theoretical concept has become central to research on the economics of energy policy (Markusson and Haszeldine, 2009), energy transitions (Vergragt et al. 2011; Kalkuhl et al., 2012), and automobile transportation and urban mobility (Urry, 2013; Geels, 2005). In many instances, it is difficult to

distinguish when lock-in is used as a theoretical concept versus when it is being used to describe empirical phenomena; this is part of its ubiquity and versatility across contexts and disciplines.

We contend that lock-in is relevant beyond fossil fuels and energy infrastructure to a much broader range of multi-scalar and intersectional socio-environmental challenges across geographically diverse contexts in which it has been typically deployed. The concept of feeling "trapped" into certain technologies, behaviors, and/or relations emerges across contexts and in public and policy discourse—from the consumption of plastics and palm oil to structural racism and poverty. Unsurprisingly, lock-in has analogues within research in economics, rural development and agrarian change, sociology, political ecology, and political science, where similar phenomena are variously referred to as "path dependency", "poverty traps", "debt traps", "institutional dependency", and "maladaptation." These terms have been especially important across socio-economic contexts, including water governance (Sehring, 2009), fisheries (Laborde et al., 2016), and farm tenure and debt (Stone and Flachs, 2019). Across contexts, scholars struggle to contend with deterministic and intransient relations, behaviors, and attitudes that conflict with the objectives of sustainability, equity, or efficiency. Lock-in thus underlies structural conditions that are seemingly inescapable and, unlike other types of social and environmental challenges, are typically cast as intractable (Haider et al., 2021; Urry, 2004).

How do we know if we are "locked-in" and how might locked-in dynamics ultimately be disrupted? Is lock-in ever a good thing, or is it always a case of intractable sub-optimal conditions? What criteria and whose perspectives determine which outcomes are sub-optimal? At what scale(s) can and should lock-in be assessed: is it always most pertinent to global scale infrastructure, such as for fossil fuels, or can the theoretical concept be applied to explain more localized empirical phenomena? Can something be locked-in at one scale but not at another?

More comprehensive analysis of the recurring phenomenon of entrapment and the arguments furthered in the literature for why certain situations—technologies, behaviors, and relations—become entrapped, and whether lock-in occurs as a gradual, cumulative phenomena or occurs acutely at a critical juncture, is important for identifying consensus, policy interventions, and the potential for collective action. Indeed, not all challenges, or all aspects of all challenges, represent lock-in that we consider intractable. As such, better understanding can help guide diagnostic evaluations and perhaps allow us to envision solutions to problems that we may have previously viewed as locked-in.

This review provides an overview and integration of concepts analogous to lock-in from across disciplines (Table 1, next section), thus integrating approaches, harmonizing concepts, and promoting a more thorough concept of lock-in. We argue that assessing how different fields analyze lock-in identifies cross-cutting themes and reasons for why, how, and when lock-in emerges. This work broadens the utility of lock-in beyond carbon (Table 2, section 4), and strengthens our analytical ability to understand entrenchment in complex socio-environmental systems. This is because it helps integrate not only the technology-centric aspects of lock-in that are the focus of much of the lock-in literature (e.g., climate change lock-in through fossil fuel dependence and associated institutions and social relations), but also the cultural, historical, institutional, and power dynamics better recognized by other fields (e.g., sociology, political science, political ecology, and critical agrarian studies). Importantly, our review draws on political ecology and proximate social science conversations to recognize how power and social relations emerge across local, regional, and international scales, while also taking seriously the discursive-material interplay of environmental problems (Robbins 2011; Svarstad et al. 2018).

For this review, we conducted a guided search in the literature using key terms including and associated with lock-in and path dependency, including "poverty traps", "debt traps," "maladaptation", and "institutional dependency." Our starting point was the most current use in the climate change and energy sector literature around carbon lock-in; however, this quickly led us to earlier, foundational work in evolutionary economics and interlocking factor markets. Our review also covers debates and case examples in political ecology, agrarian studies, and within socio-technical systems and resilience thinking that have engaged concepts related to lock-in. In doing so, we seek to understand the nuances of lock-in as both a theoretical concept and an empirical outcome, and question whether and under what conditions lock-in and path dependency necessarily leads to suboptimal outcomes. We then draw out some broad but non-exhaustive conceptual themes that emerge across disciplinary literature—scale, temporality, and structural unevenness—to discuss how sub-optimal conditions develop unevenly and more fundamentally, are seen as sub-optimal, depending on the spatial or temporal lens used to analyze the problem. We also continue ongoing discussions on how to recognize what Stone and Flachs (2019) term "path-breaking" conditions, or ways to navigate out of lock-in or almost locked-in scenarios. Our intent is that this review will help scholars understand lock-in across the disciplines and its critical application in different socio-environmental and development settings.

2. LOCK-IN ACROSS THE DISCIPLINES

Concepts analogous to and convergent with lock-in have emerged across disciplines, although linkages among them have rarely been identified. We provide an overview of these concepts and related terminology (Table 1), illustrating how many of the similar factors have

been addressed by different fields, while also illustrating different disciplinary approaches to understanding the entrenchment of sub-optimal conditions. While we recognize that any attempt at drawing disciplinary boundaries can be artificial, they are nevertheless useful for informing the synthetic scaffolding upon which we build the rest of the paper. Clearly, there are significant overlaps among the disciplines: this is not surprising given the relevant applicability of lock-in and path dependency as terms across institutional and socio-technological contexts and their transdisciplinary appeal. In the following section we introduce how more traditional disciplines and fields of study, from economics, sociology, and political science to development studies and energy studies, have approached themes around the concept of lock-in. We then follow this in section three with a more in-depth review of other fields, such as political ecology, agrarian studies, and socio-environmental studies, which we argue provide more nuanced and applied contributions to the lock-in themes.

Table 1. Synthesis of lock-in and analogous concepts from across disciplines

Discipline	**Term/Concept**	**Definition**	**Contexts in which they are used**	**Key references**
A. Economics	Path dependency	Technologies and economic systems heavily determined by historical events	Sub-optimal decisions regarding technologies, state planning, economic systems, firms' choices	David, 1985, 1993; Arthur, 1989, 1990; Garrouste & Ioannides, 2001

B. Sociology	Behavioral lock-in	Behavior (e.g., of consumers) is "stuck" by factors such as habit, culture, or organization, into an inefficient or sub-optimal arrangement. These patterns/outcomes can often be traced to specific historical events.	Individual and societal behaviors, often focused on consumers	Mahoney, 2000; Barnes et al., 2004; Urry, 2013, 2014
C. Political science	Institutional path dependence/junctures; new institutionalisms; informal governance and norms	The timing and sequence of political junctures shape institutional decisions that are then too costly to reverse	Formal and informal institutional and governance arrangements	Schmidt, 2008; Pierson, 2000; Hall and Taylor, 1996; Sewell, 1996, Abbott, 1983
D. Development studies	Path dependence & poverty traps	Specific institutional arrangements become entrenched and make efforts to change difficult	Persistence of poverty; relationships between poverty and sustainability	Levi, 1997; Thelen, 1999; Thelen and Steinmo, 1992; Haider et al., 2018

E. Energy studies	Carbon lock-in	Interlocking technological, institutional, and social forces; policy inertia	Carbon economies and infrastructures in the context of climate change, including both societal choices and individuals' decisions (e.g., cars). Applied to energy policy; fuel transitions, and infrastructure investment	Unruh, 2000; Bouzarovski and Haarstad, 2019; Foxon et al., 2005; Bertram et al., 2015; Klitkou et al., 2015; Seto et al., 2016
F. Political ecology	Marginalization; structural uneven development; maladapataion	Sub-optimal choices observed as a factor of uneven development, marginality of peasants, and other forms of social differentiation	Conservation policy and practice; control and access of natural resources; environmental degradation	D'Alisa and Kallis 2016; Watts, 2015; Blaikie and Brookfield, 1987; Hecht, 1985; Peluso, 1992; Fairhead and Leach, 1996
G. Agrarian studies	Interlocking factor markets; debt traps; poverty traps; land dispossession	Powerful social agents control capital and create interlocking relations with rural communities that shape livelihoods and wellbeing	Land use policy and land tenure; smallholder agrarian production; capital-intensive agricultural production	Bhaduri, 1973, Bharadwaj, 1985; Bardhan, 1980; Harriss-White, 2003, 2008; Hart, 1986, 2002; Akram-Lodhi and Kay, 2010

H. Socio-environmental Systems	Panarchy; maladaptive rigidity traps; complexity theory; path re-orientation	Socio-environmental systems are pushed into fundamentally new states due to exogenous factors *contra* lock-in	Environmental governance; landscape and ecosystem change; ecosystem adaptation and resilience	Mendez et al., 2019; Holling and Gunderson, 2010; Barnett et al., 2015; Burch, 2010

2. Path Dependency, and Behavioral and Institutional Lock-in

2.1 Early debates in economics

Debates around path dependency first emerged in the mid-1980s to early 1990s in the economics literature (Table 1A). This work highlighted the role of history in shaping institutions, innovation, and industrial regulation with respect to economic production. Two path dependency proponents of that time, Paul David and Brian Arthur, point out in a series of articles that "suboptimal" or inefficient technologies can become locked in as industry standards and "these inefficiencies may persist for extended periods of time" (Barnes et al., 2004, 371; see David, 1985; Arthur, 1989; Arthur, 1990). Path dependency theorists hold that economic systems, whether state-planned or industry-based, cannot be observed outside of history or as developing "independently of previous events" (David, 1993). Arthur (1989) lauds the benefits of adopting innovations, whereas David (1985) shows that 'technology lock-ins' impede shifts toward more efficient practices. This path dependency thinking became a method to understand long-term systems through past historical events, influencing disciplinary thinking in political economy and international relations, geography and agrarian studies, and sociology (Garrouste et al., 2001; Thelen and Mahoney, 2015).

In its focus on technological trajectories, the economics literature on path dependency captures how historical events can pre-determine what comes next (David, 1993; Arthur, 1989).

According to David (1993, 10), one "cannot escape through the intervention of some external force, or shock, that alters its configuration or transformations of the underlying structural relationships among the agents." David cautions that Arthur's (1989) use of "lock-in, in which historical events are deterministic of future technological trajectories, is evidently a gloss that should not be read too literally" because determinism is too limited in scope. For these proponents, lock-in is a "way in which trapping is entered…although somewhat unfortunate, in allowing a hasty reader to suppose that the antecedent events somehow have created the local stability, or locked-in state (David, 1997, 35)." However, both stress that "historical accidents" cannot be ignored for purposes of analysis as "…the dynamic process itself takes on an essentially historical character" (David, 1985, 332). Hence, more recent studies have turned to these foundational works to escape the determinism of evolutionary economics and to incorporate Schumpeter's (1942) analysis of creative destruction (David, 1997, 36). These relate to forms of industrial organization, management, and innovation to historic, geographic, and technological regimes (Gort and Klepper, 1982; Casper and Whitley, 2004; Storz, 2008). In doing so, they remain faithful to Arthur's (1989) analysis of increasing returns to adoption as precluding the emergence of possible alternatives (Frenken et al., 2007; Boschma et al., 2013; Cecere et al., 2014), but are increasingly attentive to the dynamic relationship between firms, technology, the state, and markets, and the tensions therein (Kraft et al., 2014).

2.2 Sociology

Sociologists (Table 1B) analyze how the concepts of path dependency and lock-in have become standard-fare amongst many of those in evolutionary economics, arguing that the overuse of path-dependence without adequate definition has led to an overall misapplication of the term (Mahoney, 2000). Mahoney (2000, 507) notes that most scholars often superficially

gloss over the term with vague references to "'history matters"' or over-deterministically rely on notions that "the past influences the future." Rather, he states, "...path dependence characterizes specifically those historical sequences in which contingent events set into motion institutional patterns or event chains that have deterministic properties" (Mahoney, 2000, 511). Path dependency analysis, therefore, needs to involve the tracing of "a given outcome back to a particular set of historical events, and show how these events are themselves contingent occur" (Mahoney, 2000, 507). In effect, it is one thing to say that events are based on previous occurrences but it is yet another to see the event devoid of the theory needed to analyze it and "make objective claims about the existence of its path dependence" (Mahoney, 2000, 508).

Indeed, sociologists have instead tended to explore forms of 'behavioral lock-in' (Table 2B), which "occurs when the behavior of the agent (consumer or producer) is 'stuck' in some sort of inefficiency or sub-optimality due to habit, organizational learning, or culture" (Barnes et al., 2004, 372; see also Thelen, 1999; Pierson, 2000; Mahoney, 2000). Across the social sciences, some scholars see behavioral lock-in similarly yet divergently from 'institutional lock-in,' where it is not only up to producer or market forces to determine lock-in: consumer and behavioral sentiments and attitudes also have agency in this regard. For instance, Maréchal (2010, 1106) demonstrates how energy consumers are guided not only by irrational acts but also by "strong habits [that] tend to favor and seek out information that confirms their views, beliefs, and behaviors." Yet, the sociology literature has significant crossover with that of the next section on political science, whereas the former delves deeper into societal and individual behaviors, the latter concerns institutional arrangements and critical and historical factors or 'junctures' that help determine path dependency.

2.3 Political Science

Political scientists have also engaged lock-in (Table 1C), questioning just how much weight we give the past in determining current decision-making (Pierson, 2000; Sewell, 1996; Abbott, 1983). The focus here is on forms of formal and to a lesser extent, informal, institutional lock-in, with institutional decision-making a social process grounded in what Pierson (2000, 134) defines as a "dynamic of increasing returns", where "timing and sequence" matter; as the "costs of reversing particular actions" far outweigh maintaining the status quo. Nevertheless, some political scientists still follow a narrower definition of path dependency, arguing that there are key political and historical "junctures" shaping decision-making at the institutional level, and in turn shaping social construction (Capoccia 2016).

The concept of critical junctures has had an impact for those in political science – as well as other disciplines (Table 1) – in path dependency. Much of this work looks at how distinct moments of political decision-making may circumscribe future outcomes and "shape the trajectories of transitional processes' (Marzo 2019, 918), institutional or otherwise. Junctures or historical decision-making and/or historical events, e.g., crisis, war; toppling of governments, crop disruptions, become in one way or another, the antecedents to path-dependency. Pierson (2004, 134) discusses how these serve as junctures "…because they place institutional arrangements on paths or trajectories, which are then very difficult to alter" (as shown in Marzo 2019, 918). For instance, scholars have explained that political decisions at critical moments show "…a pattern of causation in which events or processes at one point in time strongly constrain subsequent events or processes" and therefore can be observed, "…as involving a high degree of agency, or strong structural determinism" (Brady and Collier 2010, 323; see also Pierson 2004; Capoccia 2016; Mahoney 2000).

Political scientists also have been at the forefront of key debates surrounding path dependency particularly its relationship the concept of "new institutionalisms" (see for example, Peters et al. 2005). Debates around new institutionalisms and path dependency have helped political scientists think beyond binary distinctions of "rationalist" versus "applied institutions" as discussed above, focusing instead on the different instruments and key epistemological variances found in classic understandings of historical and sociological institutionalism (Hall and Taylor, 1996) and what Schmitt (2008, 304) later calls "discursive institutionalism." This other approach—discursive institutionalism—breaks away from the "…basic premises of the new institutionalism, i.e., that institutions are in stable equilibria…" with "rationalist preferences," or "all-defining cultural norms" and most noteworthy for our discussion, "self-reinforcing historical paths" (Schmitt 2008, 304). For Schmitt (2008), discursive institutionalism highlights the importance of overlooked non-material communicative speech between the public and political actors and foregrounds the power of these ideas and interests in maintaining or creating the ideological foundations for path dependencies that lead to lock-ins – briefly, beyond just history, discourse matters. For many, discursive institutionalism provides a more dynamic "third way" in which to view institutional path dependency in political science, which up to this point was firmly rooted in the former historical institutionalism and in legacies of structural functionalism (Peters et al. 2005). It seems that for these scholars, discursive institutionalism now plays an important part alongside historical and sociological institutionalism in shaping and forming the mechanisms and epistemological differences of path dependency (Hall and Taylor, 1996). Although there remain remnants of historical institutionalism thinking around path dependency, the "…image of social causation that is 'path dependent,' …pushing historical development along a set of 'paths'" (Greener 2005, 92) has been disrupted, particularly at points of crisis or

conflict (called "critical junctures"), by the potential synthesis of new institutionalisms thinking. As we show below, the crossing over into or borrowing of disciplinary thinking from sociology, political ecology, and socio-environmental systems, may help political scientists and other scholars move forward to see 'intractability' differently as well as identify potential path-breaking opportunities.

2.4 Development Studies

Debates in development studies (Table 1D) have looked specifically at countries' political economy and national state economic planning to show how high costs of reversal at key points, and "...entrenchments of certain institutional arrangements obstruct an easy reversal of the initial choice" by certain bureaucratic groups and institutions (Levi, 1997, 28, as quoted in Pierson 2000, 252). As Margaret Levi notes:

> Path dependence has to mean, if it is to mean anything, that once a country or region has started down a track, the costs of reversal are very high. There will be other choice points, but the entrenchments of certain institutional arrangements obstruct an easy reversal of the initial choice (1997, 28).

In this regard, Thelen discusses path dependencies in the context of institutions within developing countries debating rational choice theory as compared to the more applied version found in historical institutionalism (see Thelen, 1999; Thelen and Steinmo, 1992). Development studies has engaged the lock-in concept particularly in the context of poverty and debt traps, or the "mechanisms that maintain poverty by keeping people or communities below a certain asset threshold" (Haider et al., 2018, 311; see also: Mahoney, 2000; Pierson, 2000). Such mechanisms

can include lack of access to knowledge, capital, or markets. Lade et al. (2017) develop a resilience-informed framework for understanding these types of lock-in by looking at the complex, "…multidimensional socio-ecological relationships that give rise to persistent poverty in poor agricultural communities" (2017, 1) and discuss the interactions between socio-ecological systems and the persistence of poverty. Using resilience systems thinking drawn from multiple disciplines, including psychology, socio-ecological systems, ecology, and development, they evaluate different self-reinforcing 'traps' used to understand the pathways leading to conditions of poverty. These include assumptions made about the relations between people and their environment that lead to ecological degradation through different causal models, including the subsistence trap model, the conventional poverty trap model, and the intensification trap model. Lade et al. (2017) furthermore take stock in a development-focused concept of non-linear "resilience thinking," which the authors argue avoids dangerously simplifying complex social-ecological dynamics that characterize most development situations while also accounting for the possibility of 'regime change' through poverty alleviation pathways (2017, 2; Allison and Hobbs, 2004). The concept of 'pathway' is developed in their work to show how the construction of different directions avoids historical and structural patterns that lead to poverty-focused solutions.

Haider et al. (2021) also develop a comprehensive review of path dependencies around 'debt traps' and development, accounting for many diverse analytical approaches and factors in the development literature and cognate fields of sociology, environmental sciences, and psychology. They synthesize different approaches in relation to path dependency through the idea of 'self-reinforcement' (Haider et al., 2018, 311; see also: Mahoney, 2000; Pierson, 2000). They express that the way "traps" are mobilized in current development literature is insufficient

to understand the extreme complexity of social-ecological interactions keeping rural communities and individuals in debt (Lade et al., 2019). Finally, Chandler and Reid (2016) argue that structural pathways and systems thinking completely miss the structural unevenness and effects of modernity and liberalizing economic theories of capitalism. Clearly, they are not alone in their critique: as we show below, both agrarian studies and political ecology—as well as cross-disciplinary work on socio-environmental systems—provide numerous cases of the consequences of policy discourses on resilience, adaptation, and vulnerability and their tacit links to path dependencies and lock-ins (see also Watts, 2015; Stone and Flachs, 2019).

2.5 Energy Studies and Carbon Lock-in

While contemporary use of path dependency and lock-in has arguably been most influential when thinking about entrenchment of fossil fuel infrastructure, there has recently been significant work on the frictions of path dependencies in energy transitions away from fossil fuels (Garvey et al., 2015; Mulvaney, 2019; Bouzarovski et al., 2016). Others have used carbon lock-in as a point of departure to take on capitalist and social drivers of fossil fuel entrenchment (Huber, 2013a; Bouzarovski and Haarstad, 2019) and uneven development of oil (Bridge et al., 2018; Lyall and Valdivia, 2018), including energy poverty and (in-)justice (Watts, 2005; Lu et al., 2017). Many have also engaged the relational cultural, political, and social factors that have reinforced the technological formations of path dependencies, or what Huber calls "the cultural and political structures of feeling" associated through "regimes of energy consumption" (2013b: 168; see also Bailey and Wilson, 2009).

One central concern in the energy geographies sub-field is how much fossil fuels are interwoven with locked-in, critical 'everyday' decisions over energy and future planning (Bouzarovski et al., 2016; Calvert, 2016) (Table 1E). Others stress the political, technological,

and social permanence of fossil fuel lock-ins (Bridge and Gailing, 2021; Huberb, 2013; Urry, 2013, 2014; Mitchell, 2011). There are, however, debates as to just how path-dependent society is and how we un-lock these systems (Urry, 2004). For instance, Haarstad and Wanvik (2017, 433) discuss the theoretical dangers of passing this off as a foregone conclusion and "…reproduce the narrative of the inevitability of oil that the fossil fuel industry has carefully constructed." Bouzarovski et al. (2016)'s case on post-socialist infrastructure planning, rather, speaks of "rolling path-dependencies" in order to explore how "…developments both overcome and supplant previous trajectories of transformation" (2016, 624). Bridge's work on resource geographies and carbon economies (2011) as well as Valdivia's concept of 'viscosity of oil' (2002) delve into the materiality of fossil fuels, its metabolic flows, and specific characteristics of being a particularly intransient commodity. These in turn shape infrastructural investments and fossil fuel politics. Valdivia, in her study of fossil fuels and the quelling of resistance in Ecuador, mobilizes the term 'viscosity' to describe oil's movement and how the frictions around the 'hidden aspects' of oil, "…which appear peripheral to the formal circulation of oil, are in fact constitutive of how hydrocarbon capital is enacted" (2020, 1). Valdivia's work exposes the tensions that form through a deep analysis of the materiality and context of oil including the "desires, struggles, and wagers" that shape everyday life in socio-ecological contexts (2020, 1). In tracing this, Valdivia's ethnography of oil's flow in the "hydrocarbon city" of Esmeraldas, Ecuador shows the left behind "…assemblages of desires that actualize the movement of crude oil from one place to the next" (2020, 7).

Yet Valdivia's work notwithstanding, the bulk of the research surrounding the concept of carbon lock-ins has focused on industrialized countries facing macro-level infrastructure and institutional fossil fuels path-dependency in the (post-)industrialized global north. This is quite

surprising as the concept is immediately relevant to a much broader range of multi-scalar and intersectional societal and environmental challenges across geographically diverse contexts. We caution against developing *a prori* conclusions as to whether socio-environmental challenges are locked-in, however, and encourage critical examination of the material and social relations around path dependencies that might lead to locked-in socio-environmental dynamics, or not. In the following section, we explore how analogous concepts are engaged in political ecology, critical agrarian studies, and in applied socio-environmental systems research. In contrast to how lock-in has been used emblematically to analyze fossil fuel entrenchment, path dependency in other types of socio-environmental systems often de-centers policy and technology, takes up questions of individual agency and power in relation to environmental change, and accepts that a certain amount of unruliness is not only inevitable, but welcome, as it opens avenues for path breaking.

3 Lock-in Analogies in Political Ecology, Agrarian Studies, and Socio-environmental Systems

3.1 Political ecology

Political ecology is arguably, as many scholars have demonstrated over the past several decades, a field defined by its shared theoretical and methodological commitments to post-positivism, social theory, and fieldwork-based qualitative research, rather than by its adherence to any disciplinary boundaries (Watts, 2015; Perreault et al., 2015). Political ecological scholarship has frequently used historical context to show how access and control of natural resources—inducing land, fossil fuels, forests, and water—have been unevenly produced through both structural political economic factors and local power relations. While early attention to the

social relations of (capitalist) production largely focused on Marxist class differentiation, political ecologists have since deepened analysis to include race, ethnicity, gender, and non-human approaches to understanding the roles of power and discourse in environmental change. Political ecology promotes an approach that puts human behavior in specific spatial and historical contexts and draws on a political economy framework that connects human activities to social relations of production. The role of local land managers and of the state are also central to understanding why and how environmental degradation occurs and becomes entrenched (Blaikie and Brookfield, 1987).

While path dependency and lock-in have rarely been mentioned explicitly in political ecological work, political ecologists have nonetheless analyzed how sub-optimal choices in natural resource use develop, become entrenched, and resist change through analogous concepts such as maladaptation and structural uneven development (Table 1F). As Watts' (2015) and D'Alisa and Kallis' (2016) discussions of maladaptive strategies show, many political ecologists also offer an embedded if indirect critique of path dependency and sub-optimal choices, pointing out that adaptation itself is a hegemonic discourse rooted in 'common sense' strategies for risk management, resiliency, and security, while maladaptive strategies following disasters or acute events can lock in vulnerabilities for certain groups or places despite also relying on common sense beliefs (Bassett and Fogelman, 2013). Watts argues that those mobilizing adaptation thinking draw from language in evolutionary biology and that "[t]o say that organisms adapt to their changing environments implies there are processes of adaptation and end states of being adapted" (Watts, 2015; 29; also see Adger et al., 2009; Pelling, 2011).

The limits of adaptation thinking, and the concept of maladaptation more generally, were an early catalyst for the formation of political ecology as a field in the 1970s and 80s that

emphasized cross-scalar structural political economy to explain environmental degradation (Blaikie and Brookfield, 1987). Subsequent approaches to analyzing environmental degradation in political ecology have explicitly and implicitly disrupted assumptions about path dependency and locked-in dynamics through empirical data gleaned from site-specific, long-term fieldwork. Many of these scholars show how elite-led (academic, state, economic) discourses have often exaggerated the extent of natural resource degradation and relied on *a priori* neo-Malthusian assumptions about increasing populations and poor peasant management of land and natural resources (Hecht, 1985; Peluso, 1992; Jerosz, 1993; Fairhead and Leach, 1996). Kull (2000), for instance, pushed back against narratives that rural communities were wholly responsible for Madagascar's deforestation, pointing out that simplistic explanations of population growth leading to environmental degradation overlooked landscape maintenance that has accompanied population growth (see also Fairhead and Leach, 1996).

Similarly, many political ecologists have argued that blaming degradation on poverty ignores the role that wealth (e.g. capital accumulation) plays in deforestation, as wealth can lead to acquiring more tools for deforestation. Hecht's foundational work in political ecology (1985) challenged normative assumptions that development in the Amazon would cause ecological destruction in the short-term but that economic growth in the long-term would lead to technical solutions that would then reverse development's worst environmental effects. Hecht drew connections between international capital, local elites, and environmental degradation, arguing that deforestation in the Amazon is attributable to exogenous structural factors, such as national and international pressure to expand cattle ranching that drives forest conversion, rather than explanations of irrational economic decision making, tragedy of the commons dynamics, and inappropriate land technology use. A political ecological understanding of path dependent, sub-

optimal choices as structurally embedded has thus considered international development policy, agricultural industrialization, war and famine, colonial production and its ongoing imprint on land access, and the role of institutional actors such as the World Bank and the International Monetary Fund, rather than assuming population pressure, individual criminal behavior, and cultural ignorance leads unilaterally to environmental degradation. Most political ecologists would likely agree with Jarosz's 1993 observation that "neither forest degradation nor poverty are isolated or self-perpetuating conditions. They are symptoms of agrarian change and indicate complex social conflicts over resource rights, distribution, and access" (367; see also Peluso, 1992), thus offering possibilities for shifting politics, peasant resistance, and positive environmental change. Yet political ecology's signature contribution, from seeing individual actors to exogenous structural factors as the source of maladaptive socio-environmental dynamics, also points to an implicit question about the mechanisms of lock-in from a political ecological perspective: does lock-in simply occur because of structural mechanisms operating at a different scale than lock-in as understood by other disciplines but nevertheless lead to the same adverse outcomes or is lock-in is a structural reality at all for political ecologists. This is not a tension that has been resolved—or even substantially addressed—in the literature, leaving open questions within political ecology about where, exactly, opportunities for path-breaking might occur.

3.2 Interlocking, lock in, and agrarian studies

In ways that overlap with and inform political ecology, work in agrarian studies has also sought to analyze why and how agrarian change occurs. In four decades of research, the analyses have ranged from the sub-optimal, interlocking systems detailed in the Indian sub-continent

(Bhaduri, 1973) to explain the persistence, subjugation, or marginalization of the contemporary peasantry, particularly vis-à-vis rural industrialization (Borras et al., 2009) (Table 1G). Reading lock-in and path dependency theory against critical agrarian studies thus provokes the question of what, exactly, is being or could be locked-in as sub-optimal: capitalist dynamics of agriculture production and trade, or rural poverty because of capitalist dynamics? Early work in agrarian studies that considered path dependent, sub-optimal outcomes had their basis in evolutionary economics (Bhaduri, 1973; Bharadwaj, 1985; Chandra, 1974; Patnaik, 1980; Patnaik, 1983). In Bhaduri's (1973) foundational study of interlocking factor markets, commercial and personal transactions between landowners and tenants/laborers in West Bengal are observed across one or more factor 'markets' of land, labor, and credit in a way that returns monopoly power to landowners and impedes economic and technological development.

Theoretical insights that have since accompanied field-based observations of complex and persistent labor-tying arrangements challenge the incumbent economic framing of 'market imperfections' and related assumptions of a linear transition away from interlocked, innovation-resistant relations as capitalist agriculture proliferates (e.g. Bardhan, 1980; Pearce, 1983; Bharadwaj, 1985; Olsen, 1996; Harriss-White, 2003; 2008; Lemeilleur et al., 2005; Sinha, 2020). First, evidence points to how interlocking systems and related debt traps are economically rational and maintained where viable livelihood alternatives or political intervention are lacking (see also Bhaduri, 1973; Bharadwaj, 1985; Chandra, 1974; Patnaik, 1980; 1983). Determinacy, however, is countered by observations of how the poor will extricate themselves from adverse interlocking relations when and where conditions are more favorable to do so via, for example, collective action (Bhalla, 1976), familial networks (Wells, 1981), or individual mobility (Srivastava, 1989). Second, as demonstrated by the return of sharecropping in Californian

strawberry fields to address labor shortages, increasing labor costs and the risk of worker organization (Wells, 1981) mean that a "wide range of labor tying arrangements […] co-exist with different institutional arrangements in the contemporary agrarian experience" (Hart, 1986:184).

Drawing on the ongoing relevance of Karl Kautsky's defining agrarian question—"whether, and how, capital is seizing hold of agriculture, revolutionizing it, making old forms of production and property untenable and creating the necessity for new ones"—(1988/1899, 12), critical agrarian scholars have observed the "hybrid forms" that consolidate and subsume the peasantry by increasing labor efficiency (if not technical efficiency) in ways that are compatible with industrial competitiveness but are not necessarily sub-optimal precursors to 'more advanced' forms of agricultural industrialization (Vergara-Camus, 2012; Hall, 2011; Mezzadri, 2016; Akram-Lodhi, 2007; Bernstein, 2003; Sudgen, 2019). Here, rural transformation as a unilateral process is refuted, "subject to the inevitability of what today would be called 'path-dependence'; that is to say, self-reinforcing processes" (Akram-Lodhi and Kay, 2010, 187). Although patron/client relations highlighted in earlier literature and the historic privilege of social actors is of course important, these interact with 'commodity-specific' market conditions, state, and social institutions to effect myriad interlinked processes and outcomes regarding expropriation (Hall, 1991). Other contemporary structural conditions that allow peasants to exist, if not necessarily thrive, include financialization of land and the expansion of shareholder value in agribusiness (Fairbairn, 2020; Goldstein and Yates, 2017; Green, 2019) and rural/urban migration and associated remittance arrangements (Sunam et al., 2021; Kelley et al., 2020; Peluso and Purwanto, 2018). Constraints to, and the possibilities for, resistance and transformation is the hallmark of a critical agrarian studies approach (Akram-Lodhi and Kay,

2010). This was arguably best anticipated by Hart (1998, 350), whose attention to socio-spatial change and 'everyday politics' suggests that "a procedural understanding of multiple trajectories at different societal levels provides a means of navigating between the determinism of 'only one thing is possible' and the voluntarism of 'everything is possible.'

A salient critique of path dependency, or arguably a re-tooling of its utility in agrarian contexts, is Stone and Flachs' (2019) study of path dependency in modernizing Indian agriculture. In this case, the persistence of "ox-weeding" is a practice favorable to smallholders that relies on local knowledge and social institutions but is seen as "a backward path obstructing the penetration of herbicides in the cotton sector" (2019, 1273). This example of the pressures associated with industrialized agriculture to divert farmers away from locked in, path dependent practices that they have refined over time and, ostensibly, prefer over the uptake of new technological interventions that "are plagued by erosion of local knowledge that ironically encourages even more intensive use of the technology" (1274). In this case, *path breaking* has implications for smallholders' shift to genetically modified crops and associated technological inputs that have not resulted in favorable outcomes for Indian farmers over the past several decades (see also Luna, 2020). More broadly, the authors point out that a political ecology perspective allows for a shift away from path dependency to path breaking, particularly in contexts where technological artifacts and systems are not becoming locked in as the theory of lock-in would assume (Stone and Flachs, 2019).

3.2 Lock-in and Path Dependency in Socio-environmental Systems

Interest in path dependency in the cross-disciplinary environmental social sciences is part of a growing turn towards applying models from the evolutionary and ecological sciences to

understand environmental governance and socio-environmental change (Gowdy and Baveye, 2019). Yet many scholars who have applied these concepts to empirical cases of socio-environmental change have found that path dependency by itself has somewhat limited explanatory capacity and thus have sought to expand its theoretical contours. Complexity theory and concepts such as panarchy—a framework for understanding the interplay between predictable and unpredictable cycles of adaptive change—have been used to analyze how resilient socio-environmental systems are in response to destabilizing exogenous events, effectively showing how such systems do *not* become locked-in (Burch, 2010; Holling and Gunderson, 2010; Octavianti and Charles, 2019; Ulibarri and Scott, 2019) (Table 1H). As Martin (2010, 1), an economic geographer, points out, such ideas have "affinities with the basic idea that underpins the concept of path dependence, namely, that in a nontrivial sense, history matters." He ultimately argues, however, that lock-in is a limited way of thinking about path dependent economic evolution since it emphasizes stability and continuity over change (see also Wald, 2016).

Critics of path dependency and associated concepts in environmental governance argue that suggesting a community is locked-in to an inescapable suboptimal pathway fails to account for local complexity and the deviations from lock-in resulting from small, unforeseen events (Chhetri et al, 2010; Cairns, 2014; Luna, 2020; Wilson, 2013). For instance, Mendez et al. (2019) call attention to how maladaptive "rigidity" traps—institutional regimes that promote command-and-control governance—fail to reconcile environmental conservation with economic development. Instead, such institutional regimes maximize power and profit to a degree that prevents innovative thinking and interventions, which further depresses ecosystem resilience. At a community level the "memory" of an experience and knowledge gained over time is passed on

to subsequent generations (Wilson, 2013); this can be true within institutions governing at other scales as well. Attention to the role of memory raises two salient caveats to the notion that path dependency leads inevitably to sub-optimal outcomes in socio-environmental systems. First, it suggests that path dependent constraints are a matter of perspective: the mutability of constraints depends, as Barnett et al. (2015) argue, on how one understands history and where one is positioned. Lawhon and Murphy (2012) further suggest that normative transition theories, including path dependency, are "rooted in a conceptualization of knowledge as an objective truth and a desire to derive legitimacy from westernized knowledge-claims rather than democratic principles" (362). Second, while transition theories such as path dependency presume a relatively coherent development of (eventually) entrenched paths through political, economic, technological, and ideological commitments, this belies an often-chaotic process when observed in particular cases (Vergara-Camus, 2012; Octavianti and Charles, 2019).

In a shift away from the concept's original usage, recent application of path dependency in socio-environmental case studies have de-centered technology to analyze how systems writ large have reached sub-optimal states (Staveren and Tatenhove, 2016; Laborde et al., 2016; Gerrits and Marks, 2008; Ulibarri and Scott, 2019). Lawton and Murphy (2012) call out the over-emphasis in socio-technical transition theory on technological artifacts, which over-privileges the role of elite actors, instead of socio-political relations based in specific places. The innovation-focused frame that dominated early social science attention to technology and the environment was couched largely in economic terms; the introduction of pesticides, waste management facilities, and "clean coal" were linked to directives from regulators and consumers, with pricing mechanisms as incentives for technological roll out (Cowan and Gunby, 1996; Berkhout, 2002). Taking account of broader structural dynamics Chhetri et al. (2010) attribute path dependency in

agricultural technologies, however, to production systems that are promoted by agricultural extension services, policies, and research systems, often with sub-optimal social and environmental costs (Gowdy and Baveye, 2019). Trajectories set in motion by these actors and policies can hinder farmers' responses to changing climatic conditions by locking them into certain production methods and foreclosing alternative crop types and planting dates. As Lawhon and Murphy (2012, 364) write, however, focus should shift to who and what benefits from, or is harmed, by, governance regimes in socio-technical transitions, as opposed to the governance rules, policies, and institutions in themselves. Recent attention to the role of technologies has also taken a wider view of what impedes or facilitates "technology treadmills" in agricultural contexts, such as the adoption of genetically modified (GM) crops and associated pesticide inputs (Bakker et al., 2020; Nicholls, 1997). Luna (2020) argues, for instance, that the role of local culture and societal pressures in Africa have shaped farmer decision-making around adoption that leads to self-reinforcing technologies, including the desire to be more 'modern' and the need to reduce on-farm labor costs. Furthermore, local cultural contexts can determine whether exogenous shocks provide an opportunity for path dependency *or* path re-orientation (Burch, 2010).

Within the context of climate change adaptation, another model analogous to path dependency is the socio-ecological trap, in which ecosystems are pushed past tipping points in non-linear fashion (Laborde et al., 2016; Octavianti and Charles, 2019). In one study of fisheries in the Lake Chad floodplain, large dam construction and prolonged below-average rainfall reduced water levels, negatively affecting fisheries. A simultaneous change in fishery governance enabled more canals to be built, tipping the socio-ecological system beyond its 'carrying capacity' as more canals led to more fishing despite a loss of productivity for each one

and leading to "canal lock-in" as local fishers continue to build canals despite awareness of the declines in fish yields (Laborde et al., 2016). Top-down governance was ineffective at halting canal construction, as fishers instead made decisions to build based on exogenous demand for fish, the sunk costs of canal construction, increasing demographic, and negative hydrological feedbacks in which reduced flood duration and volume all led to more canal building. Parsons et al. (2019) found similar path-dependent negative feedbacks in flood plain management in New Zealand, where path dependency reflected continuity of institutional arrangements and actors who maintain the status quo, such as agricultural property values that were protected from flood risk by state-maintained built infrastructure. Path dependency can change, however, if acute events such as floods trigger changes in policy or management practices. Similarly, over a longer duration, gradual changes in public perception and values, such as increased motivation for environmental conservation or increased awareness of a changing climate, can break path dependency by re-framing the problem (Parsons et al., 2019).

Other concepts scholars use to analyze socio-environmental systems include "delta trajectory," which tracks the non-linearity of floodplain and delta change over time and, similar to political science, "critical junctures," in which certain conditions "disrupt the particular mechanisms sustaining a path's stability" in ways that gradual climatic change do not (Octavianti and Charles, 2019, 1104). Staveren and Tatenhove (2016, 9) point out that "path dependency emphasizes future development of a system, whereas technological lock-in emphasizes a certain system state" at a present moment in time; hydrological interventions can involve both (Ulibarri and Scott, 2019). While locking in certain forms of hydrological engineering can be desirable in the short term as a strategy of managing water flow and land subsidence, built embankments and intensive water management led to an increasing amount of flood-prone land lying below sea

level (Staveren and Tatenhove, 2016; Fortier and Trang, 2013). Thus, while hydraulic engineering lock-ins have worked over short and medium timescales by providing protection from flooding and thus stimulating economic development, they have over longer timescales de-stabilized river delta systems in the Netherlands (Staveren and Tatenhove, 2016), the Mekong Delta in Vietnam (Fortier and Trang, 2013), and Jakarta, Indonesia (Octavianti and Charles, 2019), threatening ecological and economic stability in each case.

Yet some cases show that path dependency, *contrary to* the negative instances above, can be used to lock-in desirable policies and practices that lead to more positive environmental outcomes. For instance, Yona et al. (2019) found that path dependent mechanisms, including policy instruments and legislation, can lock-in renewable energy by guaranteeing long-term contracts for solar panels, which leads to self-reinforcement of solar farms through sunk costs, increasing returns, and positive political feedback (i.e. expansion of tariffs supporting solar panels beyond initial policy jurisdiction). Conversely, environmental policy can also lead to negative path dependency, as in the case of reintroducing wolves to Yellowstone National Park, where the wolves were detrimental to native plant species and overall ecosystem function (Yona et al., 2019). In both cases, path dependency is analyzed as an interlocking approach that takes into consideration how policies lead to lock-in of either optimal or suboptimal outcomes through self-reinforcing feedback loops (see also Cairns, 2014).

The role of state policy in understanding land use path dependency is particularly important in the tropics, where forest resources are frequently incorporated into state development plans, such as policies that discourage deforestation, incentivize forest clearing for pasture or agricultural plantations, or privatize property (Chavez and Perz, 2013; Vergara-Camus, 2012). Effects of policy may be indirect at local levels but set in motion by decisions made by

individual landholders. Policy is thus a "distant determinant" that becomes modified through intermediate determinants, such as rural infrastructure like road building and market access, and proximate determinants (household characteristics such as age, location, and background). Yet in the case of deforestation, Chavez and Perz (2013) found that path dependency could not be separated out from other causative factors, leading to divergent possible paths of future land use. This, along with the potential to lock-in desirable environmental technologies, suggests possible alternatives to locked-in and sub-optimal socio-environmental systems, at least at local scales. In the next section we draw on the review sections above, drawing out key insights that emerge across the literature from these diverse disciplines and contexts.

4. SYNTHESIZING LOCK-IN

Despite the diverse ways that lock-in has been conceptualized across disciplines, there are some common recurrent factors that characterize these traps and provide helpful interlinkages. Moreover, we argue that through insights aggregated from different fields it is possible to have a fuller understanding of lock-in and its analytic potential across a much broader range of multi-scalar, intersectional socio-environmental challenges and contexts than usually applied. We highlight ten overlapping themes that synthesize the diverse explanations from across disciplines for why situations, technologies, behaviors, and relations become locked-in (Table 2). Some of these are explicit in the path dependency and lock-in literatures, such as existing infrastructures and institutional processes, while others are implicit, such as elite capture and knowledge production. Indeed, disciplines such as political ecology, agrarian studies, and socio-ecological systems, which have not engaged significantly with the lock-in literature, nevertheless draw on analogous concepts and bring additional explanations for entrenchments that are often missing

from the traditional lock-in framing. Moreover, the review highlights that some key explanations for lock-in, many of which are overlapping, are offered across disciplines–some emerging independently and others in dialogue with other fields. This synthesis is thus an appeal for the various dimensions listed here to be stronger features when engaging with the concept across disciplines and contexts. Therefore, the main contribution of this is not only to broaden scholarship around lock-in by demonstrating interlinkages among and relative contributions of key disciplines to theorizing lock-in but to harmonize concepts with an aim of promoting a more thorough concept of lock-in in applied contexts.

Table 2. Synthesis of key sources for lock-in phenomena that emerge from the literature across relevant fields, highlighting key disciplinary approaches that most engage each of the reasons for lock-in *(Ag. St. = agrarian studies, Dev. St. = development studies, Econ. = economics, Energy St. = energy studies, Pol. Ecol. = political ecology, Pol. Sci = political science, Soc. = sociology, Soc-Env = socio-environmental systems)*

Sources for lock-in phenomena	**Descriptions and related mechanisms**	**Key disciplinary approaches, cf. Table 1 (Non-exhaustive illustrative examples based on our review)**
Existing infrastructures	Existing infrastructures are already established, including hard (e.g., roads, pipelines, refineries) and financial infrastructures (e.g., markets, credit). These represent sunk costs; alternatives are expensive.	● **Econ. –** engages technology in a deterministic way (Gort and Klepper, 1982; Casper and Whitley, 2004, Storz, 2008) ● **Ag. St. –** in the context of specific technologies, notably water infrastructure (Bouzarovski et al., 2016) and financial infrastructures (Fairbairn, 2020) ● **Energy St. –** focuses heavily on infrastructure, notably fossil fuel infrastructure (Unruh, 2000)

		● **Soc-Env –** emphasizes landscape interventions for hydrological management **(**Staveren and Tatenhove, 2016; Ulibarri and Scott, 2019)
Formal institutional processes	Existing processes are embedded in law, policies, bureaucratic processes, and the roles, skills, and expectations of those who operationalize them.	● **Econ. –** addresses in the context of sector specific State policy, incentives, and planning; organizational and technological choices are embedded in differentiated histories and geographic regions (Antonelli, 1997; Krafft et al. 2014) ● **Dev. St. –** bureaucratic policy arrangements difficult to reverse course (Thelen, 1999) ● **Pol. Sci. –** key policy decisions made through previous historical arrangements (Pierson, 2000) ● **Energy St. –** Techno-Institutional Complex derives from the link between technological systems and governing institutions (Unruh, 2000) ● **Soc-Env** – environmental policies that incentivize deforestation, species management, landscape mismanagement (Yona et al., 2019, Chavez and Perz, 2013; Laborde et al., 2016)
Established markets	Customary behaviors, institutional inertia, and existing networks; high entry costs as a barrier	● **Econ.** – Market innovation leans on established historical precedents (Arthur, 1989; Gort and Klepper, 1982) ● **Soc. –** Ideological prioritization of markets resists disruptive policy changes ● **Dev. St. –** uneven established market access leading to poverty traps (Haider et al., 2018) ● **Energy St. –** Development agendas tied to petroleum-based privatized, urban mobility (Foxon et al., 2005)
Available capital	Accessing capital for business-as-usual choices is easier and better established than for alternatives (e.g., credit, loan guarantees, favorable taxation, investor preferences).	● **Econ. –** Access to capital based on established relationships between firms, state, and targeted R&D incentives (Casper and Whitley, 2004, Storz, 2008) ● **Dev. St. –** multidimensional structural traps leading to poverty (Bharadwaj, 1985) ● **Energy St. –** 'Green' policy shifts follow least disruptive pathways for industry (Berti and Levidow, 2014) ● **Ag. St. –** increased financialization of land, favorable politics for investment (Fairbairn, 2020; Goldstein and Yates, 2017)

		● **Pol. Ecol. –** structural political economy promoted by institutional actors such as World Bank and IMF (Hecht 1984)
Elite capture	Elites within firms, individuals and state agencies disproportionately benefit from business-as-usual and have power over a range of relations (e.g., discourses, land agreements, political office) that maintain the status quo.	● **Dev. St. –** reinforcing capture of land and tenure assets to maintain poverty traps (Mahoney, 2000; Pierson, 2000) ● **Pol. Sci –** self-reinforcement of institutional elites through clientelism of state and private sectors (Schmitt, 2018) ● **Energy St. –** carbon transition limited by multinationals to suboptimal biofuel solutions (Reid et al., 2020) Pierson, 2000 ● **Ag. St. –** land dispossession, prioritization of shareholder value, use of debt as leverage over peasantry (Fairbairn et al. 2014, Green 2020) ● **Pol. Ecol. –** neoliberalization, roll-back of state regulation, land, and resource privatization (Peluso, 1992; Watts, 2015)
Labor availability	Current labor availability and patterns reduce the pressures to change. These patterns are set through structural actions such as accumulation and dispossession.	● **Soc. –** Reproduction of land clearance, precarious wage-labor relations and power asymmetries in bioenergy cultivation (Garvey et al., 2015) ● **Dev. St. –** top-down participatory schemes re-enforce an industrial and urban bias (Pearce, 1983) ● **Ag. St. –** primitive accumulation, hybrid forms of peasant-industrial efficiency, agricultural industrialization; migration and remittances, land dispossession (Kautsky 1988; Hart, 1986; Sunam et al., 2021; Peluso and Purwanto, 2018)
Bio-physical changes over time	Dramatic land use changes have already happened that fundamentally reshape environments and are hard to reverse.	● **Energy St. –** massive scale monocropping and land appropriation for biofuels (Reid et al. 2020; Adger et al. 2009) ● **Pol. Ecol. –** exogenous structural factors, conflict over resource use and access, chains of cross-scalar causation (Blaikie and Brookfield 1987, Hecht 1987, Peluso 1992, Jarosz 1993, Fairhead and Leach 1995) ● **Soc-Env** – carbon emissions from forest clearance; hydrological engineering (Parsons et

		al., 2019; Fortier and Trang, 2013; Octavianti and Charles, 2019)
Established consumption patterns	Established consumer and industry preferences and patterns demand existing products (e.g., cheap products, preference for cars).	● **Econ. –** investment knowledge (how to use) costs by consumers alongside physical or networked links and knowledge of use deter change (Barnes et al 2004) ● **Soc. –** (sub)urban 'social life' and its dependence on electricity, steel and petrol-based mobility, and consumption as pleasure (Barnes et al., 2004) ● **Energy St. –** The 'cost' of uncertainty over incumbent products and consumer patterns (Klitkou et al., 2015; Urry 2009, 2010)
Specific historical events/determinant junctures	Although not deterministic, histories—including specific events in time or critical junctures—establish patterns and shape outcomes. It is important to consider these in diagnosing lock-in.	● **Econ. –** markets fail because 'marginal adjustments of individual agents may not offer the assurance of optimization or the revision of suboptimal outcomes' (Lebowitz and Margolis, 1995, 206) ● **Soc. –** Contingent events leading to self-reproducing, inert processes (Mahoney, 2000, 2006) ● **Dev. St. –** regional or nation-states change or lock-in because of lack of local knowledge, skills and infrastructure inputs (Henning et al., 2013) ● **Pol. Sci –** historical structures which allow interest groups to be dependent upon each other for political survival (Greener, 2005) ● **Energy St. –** Incumbent know-how and technical competencies, along with pre-existing sunk costs and state-industry relations as contributory factors (David, 1993, Trencher et al. 2020) ● **Ag. St. –** primitive accumulation (Kautsky 1988) ● **Pol. Ecol. –** colonial relations are embedded in contemporary systems (Jerosz 1993; Kull, 2000)

Environmental values, preferences, and mental models	Certain values, preferences, and ways of viewing the environment can favor specific, established practices	● **Soc. –** Consumer behavior guided by habit (Maréchal, 2010) ● **Energy St. –** Public apathy or low priority for new energy forms seeding inertia (Trencher et al., 2020) ● **Soc-Env** – Institutional memory and historical knowledge guides decision making (Barnett et al., 2015; Wilson, 2013)
Knowledge production and discourse	Knowledge dissemination across scales and time (e.g., traditional and institutional knowledge, production, generation, and sharing). Discourse, received wisdom, consensus formation, hegemonic common sense, and dominant narratives.	● **Econ –** combination of firms, institutions, and mobile labor in knowledge exchange (Krafft et al., 2014) and discourse of migrant labor regimes (Hess et al., 2010) ● **Dev. St. –** structural inequalities (lack of access to education) which do not allow new techniques or improvements to reach or take root (Haider et al., 2018) ● **Pol. Ecol. –** erasure of local and indigenous knowledge systems, privatization and corporatization of knowledge, common sense hegemony of risk management/security/resiliency discourses (D'Alisa and Kallis 2016; Watts, 2015; Bassett and Fogelman, 2013; Stone and Flachs, 2019) ● **Soc-Env** – Normative transition theories privilege knowledge as objective truth, favoring elites; assumptions about linear pathways ignore chaos and complexity (Lawhon and Murphy, 2012; Holling and Gunderson, 2010; Burch, 2010)

4.1 *Overlapping conceptual insights across disciplines*

Across disciplines, the literatures vary in their empirical descriptions of what causes lock-in phenomena (Table 2), which can be further understood conceptually in terms of spatial scale, temporality, and structural unevenness. This is not an exhaustive list of concepts that cut across empirics and disciplines; we intend it as a useful starting point for future empirical and conceptual scholarship on identifying sources and mechanisms of lock-in and path dependency,

and for analyzing whether path-breaking opportunities exist. Below we describe three concepts that help identify the diverse sources of lock-in described across the literature that each discipline speaks to (Table 2). We recognize that these three are just a few of the many cross-cutting themes and dimensions found in the literature, and that they are not necessarily analogous to one another. Whereas spatial scale and temporality are dimensions of lock-in, structural unevenness is more of a condition enabling lock-in. However, these concepts can help us to define sets of conditions, critical junctures, or thresholds at which challenges do become locked in. For example, in the classic example of fossil fuel carbon lock-in, this can be fairly characterized as "locked" because multiple sources for lock-in exist (table 2)—and exist across spatial scales, time, and which are based on long-established structural unevenness (Unruh, 2000). But are all cases equally locked-in, in the same ways? Structured analyses of the sources of lock-in and their scales might provide not only a helpful way to not only describe phenomena but may also serve as a litmus test as to whether they are truly "locked-in" to sub-optimal dynamics and may help to envision path-breaking opportunities.

4.1.1 *Spatial Scale*

Across the diverse sources for lock-in observed in the literature (Table 2), spatial scale plays an oversized role defining contexts that are locked-in, while also helping to distinguish those that are not. First, in considering sub-optimal socio-environmental outcomes resulting from locked-in dynamics, what scale(s) matter for analysis? Analysis of potential lock-in and opportunities for path-breaking might look closely at the interplay between dynamics at a local scale, which often but not always can be attributed in part to individual actors and communities, and those that are determined by exogenous structural factors, which operate at broader (e.g. national, regional, global) scales. Work around political ecology and agrarian studies highlighted above

demonstrates that much of the dynamics of scalar differences of those (mainly local actors) under extensive social, political, and economic marginalization, and livelihood choices that result in environmental or economic crisis (e.g., soil management in Nepal (Blaikie and Brookfield 1987, Hecht 1987, Peluso 1992), shifting cultivation (Jerosz 1993; Kull, 2000), investment in cash crops (Watts 2015). Yet, a broader political economic or critical development studies perspective at the regional, national, and international scale provides a clearer picture of how local level actors become seemingly locked-in to poor environmental conditions and left with few path-breaking opportunities (Stone and Flachs, 2019). Furthermore, as many political scientists and development studies scholars have observed, lock-in at the local level is often a result of structurally uneven institutional policies at the national and international level (Bassett and Fogelman, 2013).

Second, adverse socio-environmental dynamics might seem more entrenched at larger scales than at smaller, more localized ones: the complexity involved in systems that operate at global scales, such as capitalism, global energy infrastructure, or food supply, may make them more locked-in, given the redundancy built into more complex systems (e.g. more dynamics or mechanisms need to be reversed or disrupted for the entire system to shift). For instance, recent studies in socio-economic systems around the global production of palm oil provides a quintessential case of this (Taheripour et al. 2019, Rulli et al. 2019, Jelsma et al. 2017). A mixture of consumer and industry preferences and political economic drivers of global food supply chains show the scalar differences of lock-in. While some dynamics of this system may seem locked-in at one level—for instance, global and regional demand—others not be at the local scale, since in areas of intensive palm production (e.g. Indonesia and Malaysia) smallholders may be more adaptable in pivoting away from commodity cash crops, such as oil

palm, more easily than regional or national institutional and private sectors firms which have heavily invested capital in production (Zhao et al. 2022, Santika et al. 2019).

Last, lock-in mechanisms operating at one or more spatial scales may or may not enable locked-in outcomes at the same scales. A suboptimal outcome at one scale, for instance, might be inextricably tied to more optimal outcomes at other scales, both for people and ecosystems, as the literature stressing the importance of positionality shows (Barnett et al. 2015; Lawhon and Murphy 2012). If a species becomes locally extinct within an ecosystem but other populations still inhabit ecosystems in other regions – how are these two differing outcomes, at a given point in time, conceptually related or outcomes of a broader, or more localized, processes?

4.1.2 Temporality

Temporal scales are also often used to characterize lock-in, and Mahoney (2000, p. 537) challenges analysts to develop more objective criteria for "determining what temporal point should represent the 'initial' or 'starting' conditions of a sequence" that lead to lock-in and path dependency. Niche innovations and small-scale changes are found to be 'the foundation' of big transitions observed in the energy sector. 'Phases' of adaptation, gradual standardization, attainment of economies of scale, and subsequent diffusion require decades or indeed century-long periods for transitions (Grubler, 1996). Given the centrality of energy and fossil fuels to societal infrastructures and practices, it is unsurprising that this sector features poignantly in studies of how behaviors (sociology), regulatory institutions (economics), liberal ideologies (political ecology; socio-environmental studies), technical systems (energy studies) impede the pace of change with resistance to, or co-option of, new ideas a hallmark of powerful interests (political economy).

However, where sources of lock-in (Table 2) undergo alterations simultaneously, rapid shifts are possible (Geels, 2005), highlighting the importance of critical junctures. For example, in agrarian studies, research on the green revolution shows sources of lock-in (technological change, new regulatory environments, political lobbies and market incentives) locked into a model of industrialized, chemical input intensive export-oriented monocultures, in which co-option and coercion of producers was integral (Fairbairn, 2020; Goldstein and Yates, 2017). This example highlights the utility of lock-in as an analytical tool that is most helpful when looking retrospectively to identify critical junctures and acute events that led to significant shifts, but potentially less convincing when determining future trajectories, prone as many systems are to unpredictable shock and sudden disruption.

Here, however, the notion of a critical junctures (e.g., drought events, war, pandemic) offers a temporal lens for communication across disciplines to understand lock-in and openings for path-breaking. While there is growing consensus across scales, institutions, and populace that locked-in scenarios are suboptimal, there are examples of how aggressive state planning, with key stakeholder involvement, has responded to specific events (e.g., scarcity, accidents, environmental disasters, global crises) with sudden disruption to apparently locked in technologies, infrastructures, and practices (Sovacool, 2016).

4.1.3 Structural Unevenness

Structural unevenness concerns the recognition of existing arrangements of organizations, institutions, and societies and their power over access to knowledge, resources, technology, and infrastructure (Neimark et al. 2000). Structural unevenness is a key conceptual theme across fields that links multiple sources of lock-in. It is overtly recognized in some fields, notably political ecology and agrarian studies. However, it is often less visible in some other fields of

study such as political science and sociology (Table 1), yet recurrently appears as a determinant of the (in-)ability to respond and/or recover from specific historical events or junctures (e.g., shifts in technology from fossil fuels to renewables, crop boom and busts, social strife, or war). It also captures how the "winners and losers" of the resulting lock-ins are determined (Lebowitz, and Margolis, 1995; Mahoney, 2000; Henning et al., 2013; Haider et al., 2018; Watts, 2015; Bassett and Fogelman, 2013; Stone and Flachs, 2019).

Many disciplines hold similar frameworks and points of departure for understanding structural unevenness within lock-in. For instance, discussions in political ecology surrounding institutional bureaucracies in the Global South that were beholden to neoliberal structural adjustment policies designed by global finance institutions, explain how these led to unevenness in sources of lock-in such as established markets, labor availability, and elite capture—at times leading to poverty traps (Hecht, 1984; Peluso, 1992; Watts, 2015). Development studies (Haider et al., 2018) and economics (Hess et al., 2010) observe similar patterns across scales and time. In political science as well, there are ways in which institutions are studied and understood in how they both adopt and roll out new practices, infrastructures, technologies, and policy (Peters et al. 2005).

Finally, our synthesis shows how there are many more sources for lock-in (Table 2), often explored in other literatures in ways that may not explicitly frame it as such, but nevertheless help to sharpen the lock-in concept. For example, critical development studies, political ecology, and agrarian studies bring to light some of these specific explanations, such as consumption patterns, environmental values, knowledge production and discourse, elite capture, and labor availability, which emerge across literatures and cases (Table 2). They explore underlying issues of spatial scale, temporality, and structural unevenness, which also help to

understand lock-in in deeper ways. A nuanced and critical application of lock-in to particular, but cross-scalar, contexts may point the way. As such, other fields can provide contextual richness and ontological specificity to lock-in (i.e. it's not just the oil or the pipeline, but also the people putting in that pipeline and those benefiting from it).

This broadened view of lock-in also invites an evaluation of the underlying contestations of what is "suboptimal" about specific lock-in phenomena, as these are often a matter of perspective and positionality. While lock-in phenomena may lead to suboptimal outcomes for some, they are potentially optimal for others. A cross-disciplinary approach creates opportunities to explore "who wins and who loses" across contexts. Acknowledging contestation requires a better grasp of space and scale, and of diverse knowledge systems and practices, than have traditionally been factored into many empirical studies and analyses of lock-in. Perhaps a certain unruliness is called for: one that recognizes the utility of lock-in theory yet expands to also consider who and what is being constrained.

Conclusion: What to do with lock-in?

The traditional lock-in literature and terminology is heavily associated with elitist, techno-scientific, and institutionalist structure, yet our review also clearly highlights that entrapment phenomena are not so simple as traditionally posited. Analyzing lock-in and the potential for path-breaking within very narrow parameters of technological innovation and infrastructure might render cases similar when they are not. Yet, the lock-in concept has broad applicability and potential, especially where it borrows from across disciplines. Indeed, we feel that the lock-in concept has much to offer to identify, analyze, and find solutions to seemingly intractable socio-environmental problems, including many that have not yet been explored vis-à-

vis lock-in, from suboptimal phenomena like environmental racism and food insecurity to more optimal phenomena like climate change-responsive infrastructure. We hope that this review can help with cross-disciplinary communication and learning (Table 1) and more thorough and structured analyses of phenomena (Table 2, Section 4.1), including to help develop new forms of "path breaking" or solutions to both the framing and construction of the casual observance of lock-in (Stone and Flachs, 2019), Furthermore, we see this review as non-exhaustive and call for others to add to or qualify the limited variables we have included in this article.

We revisit three questions posed in the introduction about lock-in's analytic potential:

How do we know if we are "locked-in"?

We put forward a range of explanations for what might constitute a lock-in, and Table 2 can help guide analyses of specific situations. Importantly, there may be explanations or variables from other disciplines and literatures that speak to similar phenomena and offer helpful insights, but which may be unfamiliar to disciplinary scholars. That said, not all the explanations transfer or are the most salient in all situations. We know that "history and context matter" (cf. Mahoney, 2000), but not all matter equally to all contexts. Scale and positionality also matter for determining whether something is locked-in, suggesting that lock-in is not always (or ever) an inherent truth but a matter of how a dynamic is analyzed and by whom. Assessing whether something is locked-in is also about a matter of degree: dynamics are not necessarily locked-in within a binary register but may fall along a spectrum of lock-in and at times shift along that spectrum. Furthermore, this review has indicated that lock-in may occur along critical junctures in which a phenomenon could have become more entrenched or led to highly adverse outcomes but instead led to outcomes that were not 'as bad' as they could have been.

If we do not have the multiple hypotheses, lenses, and explanations at our disposal (often because of disciplinary limits), then our research is at a disadvantage. However, as the section on political ecology through to socio-environmental literature illustrates, the need to grasp the material and social dimensions of lock-in and path dependency is recognized by many scholars, even if the dynamics at hand are not always referred to as such. There is, encouragingly, growing evidence of dialogue across disciplines, particularly regarding climate change, that refines understanding of lock-in across scales and systems (e.g. political economic, technological, and ecological) in ways that both refine understanding of whether a system is locked-in and, helpfully, offer new ways of thinking about unlocking lock-in (Duvat et al., 2021; Marquardt and Masiritousi, 2021; Bernstein and Hoffman, 2019).

Is lock-in ever a good thing, or is it always a case of intractable sub-optimal conditions?

The literature typically frames lock-in as negative and intractable, however the review highlights that not all cases are locked-in, not all lock-in is negative for all, and path-breaking is not necessarily emancipatory. This, however, only becomes clear when we interrogate the various sources for lock-in and consider that lock-ins can have uneven costs and burden for different actors. For example, lock-in to global production systems for large-scale oil palm agriculture, as has been taken up across much of Southeast Asia, South America, and Africa, is not necessarily a burden for the industrial agribusiness producers, managers, and processors, whereas for a smallholder coerced into selling their land to an oil palm company, this lock-in leads—not inevitably but irreversibly—to social and economic conditions of dispossession. Notably, the review highlights the importance of scale and temporality in determining whether a policy, technology, or set of social relations is locked-in, and at what scale and timespan sub-optimal outcomes occur: what is so at a local scale is not necessarily locked in at a larger scale

and vice versa, and what is beneficial or suboptimal for one actor or institution is not evenly experienced by others. Additionally, there are instances where lock-in may yield benefits at different scales and time frames. As Yona et al. (2019) show, lock-in and path dependency do not always or inherently lead to sub-optimal outcomes: it can be used to entrench desirable policies, systems, or technologies. This is and will be salient in assessing transitions away from fossil fuels and towards renewable energy at multiple scales.

How do we unlock lock-in?

Evidence of "path-breaking success" is limited across the literature. This likely reflects a general tendency in the social sciences—particularly in sociology, political ecology, and critical agrarian studies—to critique and analyze empirical dynamics that have adverse impacts and outcomes, especially for marginalized communities (of which, to be fair, there are many examples). Indeed, lock-in and its related concepts are usually used analytically and retrospectively, rather than as a forward-looking, solution-oriented tool. Yet, the concepts are important for identifying approaches to unlocking lock-in in practice. Most plainly, the literature reinforces that we cannot solve complex problems with simple solutions, nor can they be solved by layering on too much complexity. Comparatively narrow approaches to framing lock-in are likely to provide correspondingly limited options for “unlocking” those challenges. Explanations of lock-in that are over-reliant on technological artifacts and/or historical events as explanations may risk identifying analogue solutions that are over-reliant on new technologies (e.g., techno-fix) or the “erasure” of history. It follows that broader approaches to conceptualizing lock-in may offer equally more solutions to moving away from suboptimal situations, technologies, behaviors, and relations. Better understanding of the recurring phenomenon of entrapment and the arguments furthered in the literature for why certain dynamics become entrapped is important

for identifying consensus, potential policy solutions, resistance, and collective action (e.g., Stone and Flachs 2019; Barnes et al., 2022). Approaches that use path dependency to orient towards desirable future outcomes and then use path dependency to work backwards using 'applied forward reasoning' may also offer a way out of lock-in (Levin et al., 2012).

Moreover, more structured analyses of lock-in that consider the multiple sources of lock-in (Table 2) and their spatial, temporal, and structural scales, may highlight opportunities and risks associated with path-breaking attempts. For example, there are several attempts to break the lock-ins associated with industrial palm oil agriculture in Indonesia, including boycotts of palm oil products (e.g., Greenpeace 2022). Analysis is likely to initially highlight the obvious lock-ins to specific agricultural technologies (palm oil), infrastructures (mills, plantations) and markets (cheap oil for many products) (Table 2). Importantly, however, there are also large-scale, long-term, and irreversible lock-ins associated with the biophysical conversion of landscapes to industrial oil palm (Table 2). Notably, the land bank associated with palm oil is already degraded and, in many cases, almost irreparably (Goldstein 2016) that path-breaking attempts to move away from palm oil lock-in might simply lead farmers to pick another cash crop, resulting in "path hopping" within a larger set of entrenched dynamics (i.e. globalized industrial agriculture) rather than path-breaking.

Indeed, we recognize the need to navigate between overly optimistic accounts of local actions on one hand and recognition of the magnitude of larger-scale, long-term, structurally uneven lock-in on the other. Path-breaking may yet occur after irreversible suboptimal outcomes have already occurred. For example, a transition from clear-cut deforestation to tree planting due to any number of factors may represent a positive shift for local people and environments—a path breaking opportunity—but only after forest biodiversity has been lost irreversibly.

Furthermore, there may be cases where, at present, sub-optimal outcomes resulting from path dependent dynamics are—indeed—locked in, despite path-breaking opportunities in the present: any transition to renewable energy systems and associated emissions reductions will occur alongside the excess carbon dioxide already in the atmosphere, with ongoing catastrophic, locked-in consequences. Where there are multiple types of lock-in across different scales, there may not be a viable way out. However, broader and more systematic analyses of lock-in phenomena may help us to identify which challenges can and should be overcome, and on which explanations we should focus our attention.

Funding

Benjamin Neimark was funded by a UKRI-Economic Social Research Council Award (No. #A106153).

Acknowledgements

Thank you to two anonymous reviewers for their suggestions that strengthened this manuscript. We would also like to thank Arun Agrawal for his early encouragement which was invaluable for pushing our initial ideas around this subject forward.

References

Abbott, A. (1983). Sequences of social events: Concepts and methods for the analysis of order in social processes. *Historical Methods: A Journal of Quantitative and Interdisciplinary History, 16*(4), 129-147.

Akram-Lodhi, A.H & C. Kay (2010). Surveying the agrarian question (part 1): unearthing foundations, exploring diversity, *The Journal of Peasant Studies, 37*(1), 177-202.

Akram- Lodhi, A.H. (2007). Land Reform, Rural Social Relations and the Peasantry. *Journal of Agrarian Change, 7*, 554-562.

Allison, H. E., & Hobbs, R. J. (2004). Resilience, adaptive capacity, and the "Lock-in Trap" of the Western Australian agricultural region. *Ecology and Society, 9*(1), 1-25.

Antonelli, C. (1997) The economics of path-dependence in industrial organization *International Journal of Industrial Organization, 15,* 643-675

Arthur, W. B. (1989). Competing technologies, increasing returns, and lock-in by historical events. *The Economic Journal*, *99*(394), 116-131.

Bakker, L., van der Werf, W., Tittonell, P. A., Wyckhuys, K. A., & Bianchi, F. J. (2020). Neonicotinoids in global agriculture: evidence for a new pesticide treadmill? *Ecology and Society*, *25*(3), 26.

Barnes, A.P., J. McMillan, L.A. Sutherland, J. Hopkins, S.G. Thomson. (2022). Farmer intentional pathways for net zero carbon: Exploring the lock-in effects of forestry and renewables. *Land Use Policy*, *112*, 105861

Barnes, W., Gartland, M., & Stack, M. (2004). Old habits die hard: path dependency and behavioral lock-in. *Journal of Economic Issues*, *38*(2), 371-377.

Barnett, J., L.S. Evans, C. Gross, A.S. Kiem, R.T. Kingsford, J.P. Palutikof, C.M. Pickering, S.G. Smithers. (2015). From barriers to limits to climate change adaptation: path dependency and the speed of change. *Ecology and Society, 20*(3), 1-11.

Berkhout, F. (2002). Technological regimes, path dependency and the environment. *Global Environmental Change, 12*, 1–4.

Bernstein H. (2003). Farewells to the peasantry. *Transformation: Critical Perspectives on Southern Africa, 52*, 1–19.

Bernstein, S., & Hoffman, M. (2019). Climate politics, metaphors and the fractal carbon trap. *Nature Climate Change*, 9, 919-925.

Bertram, R. M., Blase, K. A., & Fixsen, D. L. (2015). Improving programs and outcomes: Implementation frameworks and organization change. *Research on Social Work Practice*, *25*(4), 477-487.

Bassett, T.J., Fogelman, C. (2013). Déjà vu or something new? The adaptation concept in climate change literature. *Geoforum*, 48, 42-53

Berti, P. and Levidow, L. (2014). Fueling expectations: A policy-promise lock-in of UK biofuel policy, *Energy Policy, 66*, 135-143.

Bhaduri, A. (1973). A Study in Agricultural Backwardness under Semi-Feudalism. *The Economic Journal*, *83*(329), 120-37.

Bhalla, S. (1976). New Relations of Production in Haryana Agriculture. *Economic and Political Weekly, 11*(3), A25-30.

Bharadwaj, K. (1985). A View on Commercialisation in Indian Agriculture and the Development of Capitalism. *Journal of Peasant Studies*, *12*(4), 7-26.

Blaikie, P. & Brookfield, H. (1987). *Land Degradation and Society.* Routledge.

Boschma, R., Minondo, A. and Navarro, M. (2013). New industries and relatedness in regions. *Economic Geography*, *89*, 29-51.

Bouzarovski, S., & Haarstad, H. (2019). Rescaling low- carbon transformations: Towards a relational ontology. *Transactions of the Institute of British Geographers*, *44*(2), 256-269.

Bouzarovski, S., Sykora, L., Matoušek, R. (2016). Locked-in post-socialism: rolling path dependencies in Liberec's district heating system. *Eurasian Geography and Economics*, 57(4-5), 624-642.

Bridge, G. (2011). Resource geographies 1: Making carbon economies, old and new. *Progress in Human Geography, 35*(6), 820-834.

Bridge, G., Özkaynak, B., & Turhan, E. (2018). Energy infrastructure and the fate of the nation: Introduction to special issue. *Energy Research & Social science*, 41, 1-11.

Bridge, G., & Gailing, L. (2021). New energy spaces: Towards a geographical political economy of energy transition. *Environment and Planning A*, 52(6), 1037-1050.

Burch, S. (2010). Transforming barriers into enablers of action on climate change: Insights from three municipal case studies in British Columbia, Canada. *Global Environmental Change, 20*, 287–297.

Cairns, R. C. (2014). Climate geoengineering: issues of path- dependence and socio- technical lock- in. *Wiley Interdisciplinary Review of Climate Change, 5*, 649–661.

Calvert, K. (2016). From 'energy geography' to 'energy geographies' Perspectives on a fertile academic borderland. *Progress in Human Geography*, 40(1), 105-125.

Cecere, G, Corrocher, N., Gossart, C. and Ozman, M. (2014). Lock-in and path dependence: an evolutionary approach to eco-innovations. *Journal of Evolutionary Economics*, 24(5), 1037-1065

Chandler, D., & Reid, J. (2016). *The neoliberal subject: Resilience, adaptation, and vulnerability*. Rowman & Littlefield.

Chandra, N. (1974). 'Farm Efficiency under Semi-Feudalism: A Critique of Marginalist Theories and Some Marginalist Formulations', *Economic and Political Weekly*, Aug., 1309-32.

Chavez, A. B. & Perz, S. G. (2013). Path dependency and contingent causation in policy adoption and land use plans: The case of Southeastern Peru. *Geoforum, 50*, 138–148.

Chhetri, N. B., Easterling, W. E., Terando, A. & Mearns, L. (2010). Modeling Path Dependence in Agricultural Adaptation to Climate Variability and Change. *Annals of the American Association of Geographers* **100**, 894–907.

Cowan, R. & Gunby, P. (1996). Sprayed to Death: Path Dependence, Lock-in and Pest Control Strategies. *The Economic Journal* **106**, 521.

D'Alisa, G., Kallis, G. (2016) A political ecology of maladapatation: Insights from a Granscian theory of the State. *Global Environmental Change* **38**, 230-242.

David, P. A. (1997). Path dependence and the quest for historical economics: one more chorus of the ballad of QWERTY. Discussion Papers in Economic and Social History Number 20, Oxford: Accessed https://www.nuffield.ox.ac.uk/economics/history/paper20/david3.pdf

David, P. A. (1994). Why are institutions the 'carriers of history'?: Path dependence and the evolution of conventions, organizations and institutions. *Structural Change and Economic Dynamics*, **5**(2), 205-220.

David, P.A. (1985). Clio and the Economics of QWERTY. *American Economic Review*, **75**(2), 332-37

David, P.A. (1993). Historical Economics in the Long Run. In *Historical Analysis in Econometrics* (G.D. Snooks, ed.). London: Routledge.

Duvat, V.K.E., N. Volto, L. Stahl, A. Moatty, S. Defossez, J. Desarthe, D. Grancher, V. Pillet. (2021). Understanding interlinkages between long-term trajectory of exposure and vulnerability, path dependency and cascading impacts of disasters in Saint-Martin (Caribbean). *Global Environmental Change, 67*, 102236

Fairbairn, M. (2020). *Fields of Gold: Financing the Global Land Rush*. Ithaca, NY: Cornell University Press

Fairbairn, M. *et al.* (2014). Introduction: New directions in agrarian political economy. *Journal of Peasant Studies 41*, 653–666.

Fairhead, J. & Leach, M. (1996) *Misreading the African Landscape: Society and Ecology in a Forest-Savanna Mosaic.* Cambridge University Press.

Fortier, F. & Trang, T. T. T. (2013). Agricultural Modernization and Climate Change in Vietnam's Post- Socialist Transition. *Development and Change, 44*, 81–99.

Foxon, T. J., Gross, R., Chase, A., Howes, J., Arnall, A., & Anderson, D. (2005). UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures. *Energy Policy*, 33(16), 2123-2137.

Frenken, K. Van Oort, F. and Verburg, T (2007) Related Variety, Unrelated Variety and Regional Economic Growth. *Regional Studies*, *41*(5), 685-697

Garrouste, P., & Ioannides, S. (Eds.). (2001). *Evolution and path dependence in economic ideas: past and present*. Edward Elgar Publishing.

Garvey, B., Tyfield, D., & De Mello, L. F. (2015). 'Meet the New Boss… Same as the Old boss? 'Technology, toil and tension in the agrofuel frontier. *New Technology, Work and Employment*, *30*(2), 79-94.

Geels, F. W. (2005). *Technological transitions and system innovations: a co-evolutionary and socio-technical analysis*. Edward Elgar Publishing.

Gerrits, L. & Marks, P. (2008). Complex bounded rationality in dyke construction Path-dependency, lock-in in the emergence of the geometry of the Zeeland delta. *Land Use Policy, 25*, 330–337.

Goldstein, J.E. (2016) Knowing the subterranean: Land grabbing, oil palm, and divergent expertise in Indonesia's peat soil. *Environment and Planning A* 48(4): 754-770.

Goldstein, J.E. & Yates, J. S. (2017). Introduction: Rendering land investable. *Geoforum*, *82*, 209–211

Gowdy, J. & Baveye, P. (2019). An Evolutionary Perspective on Industrial and Sustainable Agriculture. *Agroecosystem Diversity Reconciling Contemporary Agriculture and Environmental Quality*, *27*, 425–433.

Green, W. N. (2020). Financial landscapes of agrarian change in Cambodia. *Geoforum* doi:10.1016/j.geoforum.2020.02.001.

Greenpeace. (2022) Oil palm: the challenges we face. https://www.greenpeace.org.uk/challenges/palm-oil/ Accessed 30 June 2022

Haarstad, H., & Wanvik, T. I. (2017). Carbonscapes and beyond: Conceptualizing the instability of oil landscapes. *Progress in Human Geography*, *41*(4), 432-450.

Haider, L. J., Boonstra, W. J., Peterson, G. D., & Schlüter, M. (2018). Traps and sustainable development in rural areas: a review. *World Development*, *101*, 311-321.

Haider, L. J., Schlüter, M., Folke, C., & Reyers, B. (2021). Rethinking resilience and development: A coevolutionary perspective. *Ambio, 50,* 1304-1312.

Hall, D. Land grabs, land control, and Southeast Asian crop booms. *Journal of Peasant Studies, 38*, 837–857 (2011).

Harriss-White, B. (2003). *India Working*: *Essays on Society and Economy*. Ithaca: Cornell University Press.

Harriss-White, B. (2010). Globalization, The Financial Crisis and Petty Production in India's Socially Regulated Informal Economy. *Global Labour Journal, 1*(1), 152-177.

Hart, G. (1986) Interlocking Transactions: Obstacles, Precursors or Instruments of Agrarian Capitalism? *Journal of Development Economics, 23*, 177-203

Hart, G. (1998). Multiple Trajectories: A Critique of Industrial Restructuring and the New Institutionalism. *Antipode, 30*, 333–356.

Hecht, S. B. (1985). Environment, development and politics: Capital accumulation and the livestock sector in Eastern Amazonia. *World Development, 13*, 663–684.

Hess S., Kleinschmit D., Theuvsen L., von Cramon-Taubadel S., and Zschache U. (2010)

Explaining Path Dependence through Discourse Analysis: The Case of Seasonal Farm Workers in Germany. In: Schreyögg G., Sydow J. (eds) *The Hidden Dynamics of Path Dependence*. Palgrave Macmillan, London.

Holling, C. Gunderson, A. (2010) *Foundations of Ecological Resilience*. Island Press.

Huber, M. (2013a). Fueling capitalism: Oil, the regulation approach, and the ecology of capital. *Economic Geography*, 89(2), 171-194.

Huber, M. T. (2013b). *Lifeblood: Oil, freedom, and the forces of capital*. University of Minnesota Press.

IPCC report 2007 - Solomon, S., Manning, M., Marquis, M., & Qin, D. (2007). Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC (Vol. 4). Cambridge university press.

Jarosz, L. (1993). Defining and Explaining Tropical Deforestation: Shifting Cultivation and Population Growth in Colonial Madagascar (1896-1940). *Economic Geography*, *69*, 366–379.

Jelsma, I., Slingerland, M., Giller, K.E., Bijman, J. (2017) Collective action in a smallholder oil palm production system in Indonesia: The key to sustainable and inclusive smallholder palm oil? *Journal of Rural Studies* 54, 198-210.

Kalkuhl, M., Edenhofer, O., & Lessmann, K. (2012). Learning or lock-in: Optimal technology policies to support mitigation. *Resource and Energy Economics*, *34*(1), 1-23.

Kautsky, K. (1988/1899). *The Agrarian Question*, 2 volumes. London: Zwan Publications.

Kelley, L. C., Peluso, N. L., Carlson, K. M. & Afiff, S. (2020) Circular labor migration and land-livelihood dynamics in Southeast Asia's concession landscapes. *Journal of Rural Studies 73*, 21–33.

Klitkou, A., Bolwig, S., Hansen, T., & Wessberg, N. (2015). The role of lock-in mechanisms in transition processes: The case of energy for road transport. *Environmental Innovation and Societal Transitions, 16*, 22-37.

Krafft, J., Lechevalier, S., Quatraro, F. and Storz, C. (2014). Emergence and evolution of new industries: The path-dependent dynamics of knowledge creation. An introduction to the special section. *Research Policy*, *43*(10): 1663-1665

Kull, C. A. (2000) Deforestation, Erosion, and Fire: Degradation Myths in the Environmental History of Madagascar. *Environment and History, 6*, 423–450.

Laborde, S. *et al.* (2016). Social-ecological feedbacks lead to unsustainable lock-in in an inland fishery. *Global Environmental Change, 41*, 13-25.

Lade, S.J., L.J. Haider, G. Engström, M. Schlüter. (2017). Resilience offers escape from trapped thinking on poverty alleviation. *Science Advances* 3: e1603043

Lawhon, M. & Murphy, J. T. (2012). Socio-technical regimes and sustainability transitions. *Progress in Human Geography 36*, 354–378.

Levi, M. (1997). A model, a method and a map. *Comparative Politics: Rationality, Culture and Structure.*

Levin, K., Cashore, B., Bernstein, S., & Auld, G. (2012). Overcoming the tragedy of super wicked problems: constraining our future selves to ameliorate global climate change. *Policy Sciences, 45*, 123-152.

Luna, J. K. (2020). 'Pesticides are our children now': cultural change and the technological treadmill in the Burkina Faso cotton sector. *Agriculture and Human Values 37*, 449–462.

Mahoney, J. (2000). Path dependence in historical sociology. *Theory and Society*, 29(4), 507-548.

Mahoney J. (2006) Analyzing Path Dependence: Lessons from the Social Sciences. In: Wimmer A., Kössler R. (eds) *Understanding Change*. Palgrave Macmillan, London.

Marquardt, J. & N. Nasiritousi. (2021). Imaginary lock-ins in climate change politics: the challenge to envision a fossil fuel-free future. *Environmental Politics*. doi.org/10.1080/09644016.2021.1951479

Markusson, N., & Haszeldine, S. (2009). 'Capture readiness'–lock-in problems for CCS governance. *Energy Procedia*, 1(1), 4625-4632.

Martin, R. (2010). Roepke Lecture in Economic Geography—Rethinking Regional Path Dependence: Beyond Lock- in to Evolution. *Economic Geography 86*, 1–27.

Méndez, P., Amezaga, J. & Santamaría, L. (2019). Explaining path-dependent rigidity traps: increasing returns, power, discourses, and entrepreneurship intertwined in social-ecological systems. *Ecology and Society 24*(2): 30.

Mezzadri, A. (2016) The informalization of capital and interlocking in labour contracting networks, *Progress in Development Studies 16*, 2: 124–139.

Mitchell, T. (2011). *Carbon Democracy: Political Power in the Age of Oil.* Verso: New York.

Mulvaney, D. (2019). *Solar power: Innovation, sustainability, and environmental justice*. Berkeley: University of California Press.

Olsen, W. K. (1996). *Rural Indian social relations: A study of Southern Andhra Pradesh*. Delhi: Oxford University Press.

Parsons, M., Nalau, J., Fisher, K. & Brown, C. (2019). Disrupting path dependency: Making room for Indigenous knowledge in river management. *Global Environmental Change*, *56*, 95–113.

Patnaik, U. (1980). Empirical Identification of Peasant Classes Revisited. *Economic and Political Weekly*, March, 483-488.

Patnaik, U. (1983). Classical Theory of Rent and Its Application to India: Some Preliminary Propositions, with Some Thoughts on Sharecropping. *Journal of Peasant Studies*, *10*(2-3), 71-87.

Pearce, R. (1983). Sharecropping: Towards a Marxist view. *Journal of Peasant Studies, 10*, 42-70.

Perreault, T., Bridge, G., McCarthy, J. (2015) *The Routledge Handbook of Political Ecology*. Routledge.

Peluso, N. (1992). *Rich Forests, Poor People: Resource Control and Resistance in Java*. Berkeley: University of California Press.

Peluso, N. L. & Purwanto, A. B. (2018). The remittance forest: Turning mobile labor into agrarian capital. *Singapore Journal of Tropical Geography, 39,* 6–36.

Pierson, P. (2000). Increasing returns, path dependence, and the study of politics. *American Political Science Review, 94*(2), 251-267.

Reid, W.V., Ali, M.K, Field, C.B. (2020) The future of bioenergy. *Global Change Biology, 26*, 274– 286.

Rulli, M.C., Casirati, S., Dell'Angelo, J., Davis, K.F., Passera, C., D'Odorico. (2019) Interdependencies and telecoupling of oil palm expansion at the expense of Indonesian rainforest. *Renewable and Sustainable Energy Reviews* 105, 499-512

Santika, T., Wilson, K.A., Meijaard, E., Budiharta, S., Law, E.E., Sabri, M., Struebig, M., Ancrenaz, M., Poh, T.M. (2019). Changing landscapes, livelihoods and village welfare in the context of oil palm development. *Land Use Policy* 87, 104073

Sehring, J. (2009). Path Dependencies and Institutional Bricolage in Post-Soviet Water Governance. *Water Alternatives*, *2*(1).

Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G., & Ürge-Vorsatz, D. (2016). Carbon lock-in: types, causes, and policy implications. *Annual Review of Environment and Resources*, *41*, 425-452.

Sewell, W. H. (1996). Historical events as transformations of structures: Inventing revolution at the Bastille. *Theory and Society*, *25*(6), 841-881.

Sinha, S. (2020) The politics of markets: Farmer–trader relations under neoliberalism in Punjab, India. *Journal of Agrarian Change, 20,* 255–269.

Srivastava, R. (1989). Interlinked modes of exploitation in Indian agriculture during transition: A case study. *The Journal of Peasant Studies*, *16*(4), 493-522.

Staveren, M. van & Tatenhove, J. (2016). Hydraulic engineering in the social-ecological delta: understanding the interplay between social, ecological, and technological systems in the Dutch delta by means of "delta trajectories." *Ecology and Society, 21.*

Stone, G. D. & Flachs, A. (2019). The ox fall down: path-breaking and technology treadmills in Indian cotton agriculture. *Journal of Peasant Studies, 45,* 1–24.

Sunam, R., Barney, K. & McCarthy, J. F. (2021). Transnational labour migration and livelihoods in rural Asia: Tracing patterns of agrarian and forest change. *Geoforum, 118,* 1–13.

Svarstad, H., Benjaminsen, T. A., & Overå, R. (2018). Power theories in political ecology. *Journal of Political Ecology,* 25(1), 350-363

Taheripour, F., Hertel, T.W., Ramankutty, N. (2019). Market-mediated responses confound policies to limit deforestation from oil palm expansion in Malaysia and Indonesia. *Proceedings of the National Academy of Sciences* 116(38), 19193-19199

Thelen, K. (1999). Historical institutionalism in comparative politics. *Annual Review of Political Science, 2*(1), 369-404.

Thelen, K. & Steinmo, S. (1992). Historical institutionalism in comparative politics. *Structuring politics: historical institutionalism in comparative analysis*, *2*, 369-404.

Thelen, K., & Mahoney, J. (2015). Comparative-historical analysis in contemporary political science. *Advances in Comparative-Historical Analysis*, *3*, 36.

Trencher, G. Rinscheid, A., Duygan, M. Truong, N. & Asuka, J. (2020). Revisiting carbon lock-in in energy systems: Explaining the perpetuation of coal power in Japan, *Energy Research & Social Science*, *69*, 101770.

Ulibarri, N. & Scott, T. A. (2019). Environmental hazards, rigid institutions, and transformative change: How drought affects the consideration of water and climate impacts in infrastructure management. *Global Environmental Change 59*, 102005.

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy*, *28*(12), 817-830.

Unruh, G. C. (2002). Escaping carbon lock-in. *Energy Policy*, *30*(4), 317-325.

Unruh, G. C., & Carrillo-Hermosilla, J. (2006). Globalizing carbon lock-in. *Energy Policy*, *34*(10), 1185-1197.

Urry, J. (2004). The 'system'of automobility. *Theory, Culture & Society*, *21*(4-5), 25-39.

Urry J. (2009). Sociology and Climate Change. *The Sociological Review, 57,* 84-100.

Urry, J. (2013). *Societies beyond oil: Oil dregs and social futures*. Zed Books Ltd.

Valdivia, G., & Lyall, A. (2018). The oil complex in Latin America: politics, frontiers, and habits of oil rule. *The Routledge Handbook of Latin American Development*. Routledge, 458-468.

Vergara-Camus, L. (2012). The legacy of social conflicts over property rights in rural Brazil and Mexico: Current land struggles in historical perspective. *Journal of Peasant Studies, 39*, 1133–1158.

Vergragt, P. J., Markusson, N., & Karlsson, H. (2011). Carbon capture and storage, bio-energy with carbon capture and storage, and the escape from the fossil-fuel lock-in. *Global Environmental Change*, *21*(2), 282-292.

Wald, N. (2016). Historical paths to current unrest: Extending the temporal lens in analysing geographies of agrarian change and conflict. *Geoforum, 76*, 38–47.

Watts, M. J. (2005). Righteous oil? Human rights, the oil complex, and corporate social responsibility. *Annual Review of Environmental Resources, 30*, 373-407.

Watts, M. J. (2015). The origins of political ecology and the rebirth of adaptation as a form of thought. *The Routledge Handbook of Political Ecology* (Perreault, T., Bridge, G., McCarthy, J., eds), 19-50.

Wells, M. (1981). Social conflict, commodity constraints and labor market structure in agriculture, *Comparative Studies in Society and History*, *23*, 679-704.

White, G. (1993). The Political Analysis of Markets. IDS Bulletin, 24(3), 4-11.

Wilson, G. A. (2013). Community resilience: path dependency, lock-in effects and transitional ruptures. *Journal of Environmental Planning and Management, 57*, 1–26.

Yona, L., Cashore, B. & Schmitz, O. J. (2019). Integrating policy and ecology systems to achieve path dependent climate solutions. *Environmental Sciences and Policy*, *98*, 54–60.

Zhao, J., Lee, J.S.H., Elmore, A.J., Fatimah, Y.A., Numata, I., Zhang, X., Cochrane, M.A. (2022). Spatial patterns and drivers of smallholder oil palm expansion within peat swamp forests of Riau, Indonesia. *Environmental Research Letters* 17, 044015

Prof. Jenny Goldstein, declarations of interest: none
Prof. Ben Neimark, declarations of interest: none
Prof. Brian Garvey, declarations of interest: none
Prof. Jacob Phelps, declarations of interest: none