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Sociotechnical stability and equilibrium

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Research on sociotechnical transitions depends on the identification of stable sociotechnical systems (STS) and evaluating when, why, and how they change. However, much research on STS includes only implicit reference to system stability. In contrast, research on social-ecological systems (SES) has a long history of investigating stability and equilibrium. In this text, we identify how stability is incorporated in SES research, and we identify three roles that equilibrium often takes in this process. We use these insights to inform our review of sociotechnical transitions literature and identify three pillars of sociotechnical stability. Reviewing literature on sociotechnical transitions through a focus on stability and equilibrium highlights important areas for future research on STS and how they change. Explicit and descriptive research on sociotechnical stability can help differentiate stochastic change from sociotechnical transition and improve understanding of sociotechnical resilience.

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Introduction

Recent calls for sustainable energy production, improved monitoring of natural resources, and enhanced transparency in environmental governance emphasize the importance of sociotechnical systems (STS) research [1–3,4•]. STS are the "interlinked mix of technologies, infrastructures, organizations, markets, regulations, and user practices that together deliver societal functions" [5•]. Sociotechnical transitions refer to integrated, multi-level changes in technologies, infrastructures, organizations, markets, and regulations that define STS [6,7]. Such transitions require synergistic changes in science, markets, engineering, and politics [8]. Literature identifies, documents, and critically assesses different forms of sociotechnical transition, but it often does not analyze sociotechnical stability [9•].

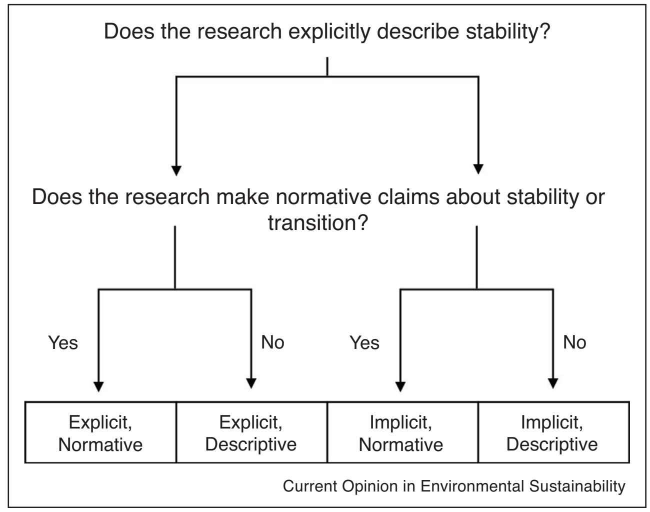
Attending to when and why STS remain stable is important for understanding sociotechnical transition. Differentiating stochastic change from system-level transition demands the definition of a stable or steady system state, and defining system-level stability often relies upon reference to equilibrium [10,11]. The identification of stability and equilibrium in natural, social, or social-ecological systems (SES) is a topic of longstanding academic debate, and it informs related literature on transition [12]. In contrast, STS research does not often focus on stability or equilibrium. For example, authors frame sociotechnical transition away from fossil fuels as a phenomenon with multiple transition pathways [13•,14,15], but they do not often investigate when tipping points occur or are absent. The identification of tipping points as moments of transition requires a definition of system-level stability [16,17]. This text seeks to motivate further study of sociotechnical stability and equilibrium to advance knowledge of how STS form, emerge, and remain over time. In turn, these insights can contribute to advancing sociotechnical transitions scholarship [9•].

In this review article, we examine stability and equilibrium within the context of SES research to inform our review of sociotechnical transition pathways and identify pillars of stability from literature on STS. In the following section, we consider how research incorporates concepts of stability and the different forms equilibrium takes. In the third section, we review different sociotechnical transition pathways and assess their relationship to stability and equilibrium. In the fourth section, we consider three pillars of sociotechnical stability that emerge from the STS literature. Together, these sections review recent research and emphasize the promise of explicit and descriptive study of sociotechnical stability.

Stability and equilibrium in social-ecological systems research

Scholarship on social and ecological stability are foundational to SES research. SES research represents systems through verbal or mathematical models that contain component variables. For example, measurements of vegetation (species richness, diversity, land cover) and livestock can represent a social-ecological rangeland system [18]. A system's state is defined by the value or condition of those variables. And stability—sometimes referred to as 'stability landscapes', 'stability domains', or 'basins of attraction'—refers to the tendency of variables to vary around an 'attractor', also known as an equilibrium [10,12]. However, SES are constantly affected by disturbance and stochasticity, and the tendency of variables to move toward an attractor can be unpredictable and unknowable. Stability in some SES research is, therefore, predicated upon a notion of equilibrium, but it is not necessarily concerned with its direct observation or measurement [11].

Figure 1



A typology for considering how systems research incorporates stability.

As a term in numerous natural and social science disciplines, equilibrium broadly refers to the balance of opposing forces. This balance is often theoretical, and it informs arguments concerning the stability as well as the transition of a system. In SES research, the theoretical as well as empirical investigation of stability and equilibrium are critical to identifying when transition occurs. Transition refers to when a system is no longer defined by variables that tend toward one or multiple attractors [11]. Thus, the first step in identifying transition requires the ability to describe stability.

Compared to STS studies, research on SES has a stronger focus on stability and equilibrium [4•]. SES research that builds from stability and equilibrium to understand transition promises to inform STS research because of the parallels between the two fields of study [19]. SES research combines insights on market dynamics, politics, culture, and other social dimensions to better understand human-environmental relationships [20,21•]. STS research similarly examines social dimensions to understand the relationship between people, politics, and technology [6,22]. To aid our discussion of stability and equilibrium, we use a basic typology to consider how research incorporates the concept of stability (Figure 1), and we identify three forms that the term equilibrium takes in SES, STS, and related disciplines (Table 1).

Equilibria as numeric values

In ecology, equilibrium for a given population is defined as the population size when its growth rate, or change over time, is zero. As such, equilibria represent discrete values that are calculated by setting differential equations to zero. In population biology, practitioners utilize logistic growth curves as simple, realistic models of population growth that produces a stable equilibrium [23]. In these models a negative feedback mechanism, such as the availability of food or the extent of predation, causes the growth rate to decline as population size increases. This growth continues until the population size eventually reaches a stasis at the stable equilibrium, commonly referred to as the carrying capacity (k).

Stability in this context refers to the tendency of variables that define a system to return to equilibria when perturbed. External perturbations may drive fluctuations around the point equilibrium, but the consequence of stable equilibrium is stasis over time. Notably, the logistic model has another point equilibrium at the population size of zero; however, this equilibrium is unstable, meaning that population size will tend *away* from this point. Unstable equilibria are characterized by positive feedbacks, which cause a value to move from an original position towards infinity, zero, or towards another stable equilibria. The 'alternate attractors model' demonstrates these different definitions of equilibrium [16]. It includes the presence of a nonzero unstable equilibrium bounded by two stable equilibrium points. Ecological research uses this model to explain alternations between low and 'outbreak' levels of population abundance in tree-killing bark beetles [24], as well as alterations between seaweed and coral reef dominated ecological states [25].

Equilibrium as a numeric value also defines some research in social systems. In game theory, for example, Nash Equilibrium refers to when each player's strategy is

Table 1

Typology of equilibrium functions with examples from SES research and applications in STS literature

Form	Type	Examples from SES	Examples from STS
Numeric value	Explicit, Descriptive or Normative	- Species population models and alternate attractors [24,25] - Bioeconomic models for fisheries management [26,27] - Game theoretic resource use models [28]	- Bottom-up and top-down energy models [29•] - Infrastructure recovery models [30]
Assumption/ Comparative standard	Implicit, Descriptive or Normative	- Hardy-Weinburg Equlibrium - Punctuated equilibrium in forest policy studies [31,32] - Estimating avoided deforestation and carbon removal from carbon taxation [33]	- Estimating CO_2 reduction from removing fossil fuel subsidies [34•,35] - Governance experiments for mitigating climate change [36]
Normative value	Explicit or Implicit, Normative	- 'Half for nature' and 'global no net loss of natural ecosystem' conservation objectives [37,38]	- Debates on deep decarbonization [5•] - Calls for enhanced supply chain monitoring of tropical agricultural commodities [1]

a best response to all other players' strategies in a non-cooperative, finite game [39,40]. "The idea of the Nash equilibrium is that a set of strategies, one for each player, would be stable if nobody has a unilateral incentive to deviate from their own strategy" [41]. This idea serves as a unifying theory for many aspects of quantitative social science. Social dilemmas refer to a family of situations when the Nash Equilibrium is not a socially desirable outcome, including ecological degradation from human activity [42]. The consideration of social dilemmas through Nash Equilibrium, as with the use of stable equilibrium to inform wildlife management decisions, applies normative arguments to insights from explicit description of stability and equilibrium. Though the clarity of assumptions and limitations that formal models of equilibrium provide are useful [43], their application to large and complex systems is challenging, particularly with reference to operationalizing stability domains [44,45].

Equilibria as assumptions or comparative standards

In other research, equilibrium takes the form of a null model, an idealized state, or a comparative baseline for understanding complex real-world scenarios. 'Hardy-Weinberg equilibrium' (HWE) is a fundamental concept in evolutionary biology and population genetics that illustrates the null-model form of equilibrium [46,47]. It describes a state when evolution is not occurring [48,49]. For a system to be in HWE, a series of assumptions are implicit. These assumptions are: the population must be indefinitely large, have random mating, no mutation, no migration, no selection, and genes must behave according to basic rules of mendelian inheritance [48,49]. These assumptions do not describe real-world situations, but form a comparative baseline. Providing evidence of departure from HWE, and identifying the assumptions that are violated, comprise the first steps in research that demonstrates how real gene frequencies vary from a null expectation and produce evolutionary change. Advances in technology and data processing have altered how researchers test HWE, but its use as a null model in evolution research remains common.

Research that analyzes and measures change in large-scale social and ecological systems also includes implicit reference to stability, using the notion of equilibrium as a comparative standard. For example, political systems contain negative feedbacks that enable fluctuation of a policy or value of interest around a theoretical equilibrium point. Standard brokering between political parties and interests generate stability, and policy studies find that change typically occurs through gradual processes and incremental shifts. In contrast, 'punctuated equilibrium', a metaphor borrowed from paleobiology, describes how rapid transitions can occur due to causes exogenous to the political system or triggered from within it [31,50]. Literature that focuses on such policy transitions often implies stability, rather than theorizing, defining, and modeling it [51].

Research that identifies urbanization as a driver of global biotic homogenization similarly relies upon the intuition of equilibrium within a system. As urban areas expand in size, artificial structures replace natural land cover or ocean environments, the number of non-native and commensal species increases, and the homogenization of species compositions results [52,53]. Thus, disruption of a previous ecological stability results in biodiversity declines. Though some research seeks to understand the relationship between urbanization and species composition through causal inference, large-scale counterfactual studies between urban and rural areas, or between different urban areas, are few [54]. Perfect counterfactuals may not exist, but the intuition or assumption of stability and equilibrium that would exist in the absence of a treatment or intervention provides the foundation upon which much causal inference research is based [55,56].

Equilibria as normative standards

In some cases, explicit arguments establish the normative value of equilibrium in a system. Concepts such as the 'balance of nature' or the 'efficiency of the market' are invoked to justify management objectives or decisions. In both examples, related management goals seek to reduce human interference to promote a 'natural' stability [57,58].

The concept of a natural stability and normative equilibrium is considered problematic in many disciplines that inform SES literature. Dynamic systems are not always stable, and definitions of equilibria depend upon temporal or spatial scales. In ecological sciences, these insights led to a shift away from considering 'climax communities' an ideal upon which to base fundamental research into community dynamics or restoration management [59]. Contemporary research considers the relationship between land-use legacies and contemporary ecosystem function to better understand global environmental change, address the rapid loss of biodiversity as well as ecosystem services, and restore ecosystem integrity [60,61].

In economics, Keynesian and evolutionary approaches hold that markets may often fail to reach equilibrium between supply and demand with major implications for policy and governance [62,63]. Phenomena that inhibit changes in prices or wages, referred to as rigidities or stickiness, prohibit perfectly competitive market equilibrium between supply and demand [64]. As long emphasized in economics textbooks, real and nominal rigidities can result in aggregate markets operating in a persistent state of high unemployment in which the return to equilibrium involves substantial lags [65].

Without a natural equilibrium to manage for, applied researchers and systems managers are tasked with defining *and* defending their objectives [66]. They must use research to explicitly address how systems function and what stability is; provide normative arguments that seek to preserve it or promote transition; and justify taking specific actions [67]. In some cases, remaining within a stability domain is a management goal. In other cases, managers and advocates seek to propel systems toward alternate states, as is the case with unjust or inequitable social arrangements [68]. In research on STS, normative arguments often address the value and importance of transition; in doing so, these studies incorporate implicit and normative arguments concerning stability [4•].

Sociotechnical systems post-equilibrium

STS research devotes significant effort to typologizing categories of sociotechnical transitions [69,70,71•,72], and clear parallels exist between the types of transitions, the concepts of stability, and equilibrium. The multi-level perspective for understanding sociotechnical transition highlights the roles of niche actors (such as developers of new technologies), the dominant regime of socio-technical institutions and related actors, and the exogenous landscape beyond niche and regime actors [8]. It distinguishes between reinforcing and disrupting relationships between niche innovations, the sociotechnical regime, and landscape developments. Reinforcing relationships, which have stabilizing effects on the regime, are analogous to stable equilibria with negative feedbacks; disruptive relationships, which exert pressure and result in regime shifts, can be analogized to positive feedbacks that cause transitions away from stability (Table 2).

This second category, disruptive transitions, can be triggered by shocks, inducing discontinuous, rapid transitions resembling regime shifts or punctuated equilibrium. Examples of exogenous shocks in the literature are many. For example, a drop in fossil fuel consumption or a rise in energy prices can rapidly alter the role and viability of an alternative energy technology, exemplified by the 1970s oil crisis, which provided the impetus for German R&D programs in wind and solar technologies [7]. Policies that change or challenge the sociotechnical regime can also provide shocks to an energy system; interventions such as pollution taxes can trigger regime shifts that can be analogized to the bifurcation events seen in chaotic dynamical systems [13•].

Top-down planning and effective implementation can also rapidly change the type of energy end-users are able to consume, in addition to spurring further innovation [73,74]. In most cases, these disruptive transitions require positive feedbacks between policy, niche innovations, and the broader technological landscape [3]. The ongoing transition to low-carbon electricity generation in the United Kingdom, for example, began with an initial set of renewable energy policies, but has accelerated as those policies have gained footholds, promoted development and commercialization of low-carbon technologies, and fed back on the development of more ambitious low-carbon policies [75]. The activation of feedbacks is termed 'acceleration' [76•,77]: technologies emerge and slowly gain disperse, until decisive policy action causes a 'tipping point' [78] whereby the technology gains widespread acceptance. This final 'stabilization' after the acceleration process bears a clear resemblance to the new stable state achieved by a system moving from one equilibrium to another.

Not all sociotechnical transitions, especially those in energy systems, are defined by shocks. Less severe

Table 2

The sociotechnical transition pathways and their contributing factors, as identified by Geels and Schot [6]

Sociotechnical transition pathway	Contributing factors
Reproduction process	No landscape pressures for change and a dynamically stable regime lead to the reproduction of the current sociotechnical regime.
Transformation path	Moderate landscape pressure and underdeveloped niche innovations lead a sociotechnical regime to influence the development of technology. Innovations in this transition pathway do not disrupt the structure of the sociotechnical regime. Examples include the rise of organic food and the transition in Dutch sanitation.
De-alignment and re-alignment path	Divergent and substantial landscape change with multiple, insufficiently developed niche innovations lead to an initial disruption of the sociotechnical regime. This disruption and de-alignment is eventually re-aligned once niche-innovation becomes dominant and a new sociotechnical regime forms. An example is the American automobile transition.
Technological substitution	Strong landscape pressure and developed niche-innovations that lead to a replacement of the existing sociotechnical regime. Geels and Schot identify the transition from sailing to steamships in Britain as an example of this pathway.
Reconfiguration pathway	Distributed niche-innovations are originally adopted into the sociotechnical regime and then trigger more fundamental changes. The transition in the US from traditional factories to mass production facilities demonstrates the characteristics of this pathway.

policy changes, like a feed-in tariff relative to a carbon tax, can result in slow transitions that do not present bifurcation-like behavior [13•]. Moreover, exogenous shocks do not always trigger rapid transitions; the Chernobyl meltdown briefly strengthened anti-nuclear activism in the UK, but activists were soon overwhelmed by pro-nuclear pressure from the UK government [5•].

A great deal of research on sociotechnical transition identifies different pathways to transition, building upon the foundational pathways typology in Table 2 [6]. As with all but the first pathway in this typology, this research takes care to understand when, where, and why STS change. Increasing the evidence base of when, where, and why STS remain stable promises to test assumptions concerning transformation pathways and lend insight into STS resilience.

Sociotechnical stability

STS transitions literature often addresses stability implicitly and uses equilibrium as a comparative standard or normative value when identifying or modeling transition. Building upon insights from canonical STS research that focuses on transition [6,8], we identify three pillars of stability that can guide explicit and descriptive research for advancing knowledge of sociotechnical stability. The three pillars of stability we identify are a lack of substitute technologies (technological constancy), limited usability of new technology (sociotechnical efficiency), and sociopolitical barriers to the diffusion of new technology (path dependence).

Technological constancy refers to when technological niches do not innovate to develop new technology, or when niche-innovations are so minimal and isolated they do not diffuse within the system. The emergence and diffusion of niche-innovations requires the dispersal of ideas and production capacity [3]. Low connectivity and reduced dispersal of ideas or communication between people limits the creation of new sociotechnical relations necessary for sociotechnical transition [9•,79]. Though technological constancy may seem less relevant in a globalized and highly connected world, certain locations, populations, or periods remain defined by it. Once niche-innovation emerges and diffuses, transition increases in likelihood. However, as some STS research demonstrates, this process is not uniform. Further empirical research on where and why niche-innovation remains immature can provide insights into understanding transitions [80].

Sociotechnical efficiency refers to when technologies and their use combine to generate a regime that is more efficient than niche-innovation. Even if a new technology is more efficient in producing an outcome, its sociotechnical efficiency depends upon social dimensions that lead to user preference and uptake. The use of two-dimensional versus three-dimensional remote sensing data for monitoring and evaluating forest areas demonstrates differences in technical versus sociotechnical efficiency. Although LiDAR technology (a remote sensing technique that generates a three-dimensional profile of a given land surface) provides higher dimensional information on forest resources, it is not widely available for organizations, employees, and researchers to view and analyze [81]. Efficiencies, such as cost, availability, and familiarity lead to the continued use of two-dimensional imagery. Understanding sociotechnical efficiencies in a pre-existing STS emphasizes the importance of understanding how rules, users, and technology reinforce one another to generate regime stability [8].

Path dependence in STS, also referred to as 'lock-in' or 'inertia', is a common driver of sociotechnical stability [82–84]. Sociotechnical regimes produce multiple reinforcing processes to facilitate the use, dissemination, and stability of a STS [15]. For example, current debates about the impact of removing fossil fuel subsidies in producer countries investigate one reinforcement mechanism for fossil fuel production. By modeling the amount and value of current oil production, forecasting and comparing carbon emissions in a future with or without subsidies, and examining the symbolic value of subsidy removal for spurring transitions from fossil fuel use, these debates aim to determine how removing this economic reinforcement mechanism will contribute to climate mitigation and sociotechnical transitions for energy production [34•,35,85,86]. Path dependencies often change slowly, through incremental deviations [87]. However, the speed and scale with which sociotechnical path dependencies can change varies greatly, often depending on sociopolitical coordination, infrastructure, and sociotechnical efficiency [74]. Path dependence is not a foregone conclusion; it is constructed [88]. Studying how and where path dependence is constructed can inform future efforts to promote the stability and resilience of sustainable STS.

Developing a strong evidence base for when, where, and why STS remain stable can advance research on sociotechnical transitions and resilience within STS. Studies that explicitly describe stability within a system are necessary for distinguishing stochastic change from system transition. Investigating cases of technological constancy, sociotechnical efficiency, and path dependence can also advance study of sociotechnical resilience. Similar to stability and equilibrium, resilience is a major focus in SES research but is not a common topic of study in STS literature [89]. Research on the extent to which STS can experience perturbations or shocks before experiencing transition finds practical application in sustainable infrastructure research [90•] as well as in the conservation of STS that are more just and sustainable than niche-innovations that might disrupt them. As the trajectory of SES research demonstrates [91,92], a growing base of empirical evidence can help refine conceptual insights concerning stability and transition within a system.

Conclusion

STS research often focuses on sustainable transitions, since such transitions are critical and timely [4•,5•]. However, the identification of transition depends upon notions of stability and its associated equilibrium. Drawing on insights from SES research and the disciplines that inform it, we consider stability in STS and sociotechnical transitions literature. We advance a typology to consider how stability is incorporated into SES and STS research and identify three common forms equilibrium takes in the articulation of stability. STS and sociotechnical transition literature often rely upon the implicit and normative incorporation of stability. However, explicit and descriptive research on stability within STS promises to contribute to the important agenda of understanding of transitions in general [9•] by providing insights on where transitions do not occur and who does not participate in sociotechnical transitions. With more empirical findings concerning the stability of STS, future research will be better positioned to inform overarching theories about how and when sociotechnical transitions occur and how such transitions result in in sustained and resilient change.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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