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Agroecological Transitions: A Mathematical Perspective on a Transdisciplinary Problem

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In the face of climate change, rising hunger and mass extinctions, scholars stress the need to transition food systems from fossil fuel-dependent conventional farms to agroecological alternatives that can store carbon, improve food security and harbor biodiversity. Theory provides a systematic approach for organizing knowledge on agroecological transitions across the natural and social sciences and summarizing the primary needs of future research. This paper reviews the socio-ecological literature related to agroecological transitions from a mathematical perspective that is derived from complex systems and critical transition theory. We organize the literature according to mathematically tractable concepts, including syndromes of production, agents, barriers and drivers of change that operate across three major frameworks of analysis: socio-ecological, socio-technological and social norms and networks. Our approach embeds the current agroecological transition theory within a critical transition framework that considers the stability of peasant and capitalist syndromes in response to various inhibitors and drivers of change. We find that the majority of our theoretical knowledge of food systems change is derived from the social sciences and limited primarily to examples from the Americas. Our work suggests a need for broader regional representations of change and transdisciplinary work aimed at better understanding how biophysical factors collide with socio-political conditions to hinder or reverse food systems change. Though scale and context are important considerations, we find that theory can generate general mechanisms that link separate case studies. For example, drivers of food systems change that shift balances between the costs and benefits of peasant and capitalist modes of production may be particularly important for explaining poverty and gilded traps in agriculture. We discuss this and other lessons learned from taking a theoretical perspective on agroecological transitions.

Keywords: agroecology, food systems change, transitions, critical transition, socio-ecological theory, sustainable food systems, complex systems

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INTRODUCTION

Conventional agricultural systems today contribute largely to climate change, biodiversity loss, and resource scarcity. Our global food system (agriculture, forestry, and other land use) is responsible for upwards to 23% of all anthropogenic green-house gas emissions according to the Intergovernmental Panel on Climate Change (IPCC) (2019). Over the past 50 years, crop yields have increased by 47% along with a 500% increase in fertilizer application rates (Foley et al., 2011; Schipanski et al., 2016). This has come at the cost of over 400 marine hypoxic regions worldwide and a significant increase in N_2O emissions (a greenhouse gas 265–298 times more potent than CO_2 on a 100 years timescale) (Diaz and Rosenberg, 1995; Pachauri and Reisinger, 2007; Foley et al., 2011; Zhang, 2017). Food production simultaneously depletes and contaminates freshwater supplies due to irrigation and the leaching of excess phosphorus fertilizers, a limited resource that is itself predicted to peak as early as 2030 (Cordell et al., 2009). Additionally, heavy reliance on pesticides and herbicides has bred resistance amongst pests, weeds and disease and threatens the populations of beneficial organisms including natural enemies, predators and pollinators (Mortensen et al., 2012). Food production is also the leading cause of deforestation and habitat fragmentation for species of conservation concern, accounting for 65% of global land-use change from 1961 to 2011 (Fischer et al., 2014; Alexander et al., 2015). At the same time, crop diversity itself has dwindled so that food markets are now dominated by a small handful of commodity crops. Lack of biodiversity and intensive farming practices have eroded soils and decreased soil fertility over time (Giller et al., 1997; Altieri, 1999; Olson et al., 2017). This highly simplified global food system reduces the adaptive resilience of farms, making them vulnerable to climate variability and extreme weather events that are also increasing in degree and frequency with climate change (Schlenker and Lobell, 2010).

Food systems also face increasingly difficult social dilemmas. Pursuing high yields as the primary goal of agriculture has greatly increased the geographic specialization and concentration of production (Patel, 2013). Large and geographically concentrated monocultures are exceedingly vulnerable to climate variability and the spread of food diseases (Ploetz, 1994; Frison et al., 2011; Centers for Disease Control Prevention CDC, 2013). Global market instabilities are induced when crops fail, an occurrence that is becoming increasingly common under climate change. For example, apple prices escalated when early spring frosts wiped out most of the production in the U.S. in 2007 (Eccel et al., 2009). Coffee production has experienced similar issues in Latin America where a fungal disease that once wiped out coffee production in Ceylon in the 1880s, the coffee rust, has become increasingly problematic as climate change exposes previously protected high-altitude coffee to infection (McCook and Vandermeer, 2015). These agriculture-induced market instabilities are expressed through volatility in food prices, which has been consistently high at the global scale and is known to disproportionately affect less-developed nations (Schipanski et al., 2016). Wealthy economies can to some extent moderate their food vulnerabilities through government policies (e.g., food subsidies) and market mechanisms, though many people in wealthy countries are still susceptible to food insecurity (Schipanski et al., 2016). Meanwhile, less wealthy economies struggle to compete. As food systems have become increasingly globalized, farms have become larger, produce fewer crop types and have converted to "deskilled" labor in order to compete in global markets (Carlisle et al., 2019). As a result, global markets are flooded by cheap commodity crops that destabilize national food systems, particularly those of less wealthy nations. Direct connections between farmers and consumers in local markets are lost as mega-size corporations with global downstream supermarket distributors gain control of the food market. As global food becomes cheaper, consumers gradually abandon local food and farmers (Wilhelmina et al., 2010; Andree et al., 2014).

Scholars and many people across the world increasingly recognize that in order to address the earth's most pressing environmental and social issues, our global food system needs to transition to a more sustainable alternative. Yet the form of agriculture we should transition to remains intensely debated (Altieri et al., 2017; Fouilleux and Loconto, 2017; Newell and Taylor, 2018; Alexander, 2019). A slurry of alternative agricultures exists, each with its own history and definition of sustainability. Some of today's most popular paradigms include regenerative farming, climate-smart agriculture and organic agriculture. Organic agriculture is the oldest of these alternatives (Guthman, 1998). Sir Albert Howard is credited as its founder, an English botanist charged with educating Indian farmers in modern western farming techniques during the early 20th century (Howard, 1936; Heckman, 2006). After observing traditional farming practices in India, Howard insisted that traditional Indian farming techniques, including Indore composting, were far superior to English technologies at preserving soil fertility (Howard, 1936). Howard also believed that increased soil health was associated with increased crop nutrition and human health in local populations (Howard, 1939). These are the tenets that the Rodale Institute used to grow the organic movement in the U.S., defining sustainability primarily in terms of soil and human health (Rodale, 1949; The Rodale Institute, 2011). However, recent inclusion of concentrated animal feed operations, aquaponic and hydroponic systems have created a self-described "Real Organic Project" that maintains allegiance to soil-based organic systems and challenges what they consider co-optation of the organic label by the agri-business industry (Morath, 2018). USDA (United States Department of Agriculture) organic certification does still restrict the use of synthetic fertilizers and pesticides because of their risk to soil and human health, but few requirements outside of this may contribute to the organic movement's struggle to maintain a consistent identity (Guthman, 1998). With concerns for climate change on the rise, climate-smart agriculture emerged in 2010 from the Food and Agriculture Organization (FAO) as another alternative agriculture that defines sustainability primarily in its resilience to climate change (Food Agriculture Organization, 2010). This alternative tends to focus on technological and financial solutions, particularly financing and producing genetically modified or selectively bred varieties of crops that can maintain high yields and provide food security under drought conditions or in the presence of severe weather events and record-high temperatures (Newell and Taylor, 2018). In contrast, definitions for sustainability in regenerative agriculture revolve primarily around soil health and climate change. Though a report on "regenerative organic agriculture" released by the

Rodale Institute referred to organic agriculture and agroecology in its definition, many definitions of regenerative agriculture itself focus primarily on how soil can be managed to store carbon and mitigate climate change rather than on the social dimensions of agroecology that are described in the definition presented by the Rodale Institute (Regeneration International, 2017; Elevitch et al., 2018; Gurian-Sherman, 2019; The Rodale Institute, 2019).

The agroecology referred to is a related yet distinct alternative. Compared with conventional agricultural systems, agroecological farms seek to support biodiversity, enhance carbon sequestration, and utilize resources more efficiently by farming according to ecological principles (Altieri, 1983; Gliessman, 1990; Rosset and Altieri, 2017). To achieve this, agroecology relies on a deep knowledge of local conditions and diverse crop profiles that mimic natural systems of the growing region. These approaches offer farmers greater capacity to adapt to increasingly variable climates and reduce the risk of massive crop failures (Carlisle et al., 2019). However, agroecology is not only a science and practice, but also a social movement that explicitly pursues social justice and food sovereignty, which is defined as the right to define, access and produce culturally appropriate and ecologically sustainable food (Patel, 2009; Rosset and Altieri, 2017). Agroecological farming techniques and practices are commonly used in organic and regenerative agricultural systems, making their differentiation difficult. Although organic, regenerative, climate-smart and other alternative agriculture paradigms do not preclude and oftentimes intentionally include social justice, they are not primary elements in their sustainability definitions and as such, do not necessitate their inclusion (Altieri et al., 2017; Fouilleux and Loconto, 2017; Newell and Taylor, 2018; Alexander, 2019). In contrast, agroecology is better known for considering society as an integral component of the ecology of foods systems and explicitly stresses connections between producers and consumers, globalized markets and their effects on food sovereignty (Patel, 2009; Schipanski et al., 2016). In this paper, we first focus on literature that describes transitions to agroecology, as defined by the authors.

Agroecological transitions, like many other large-scale shifts to sustainability, will be difficult because they require an understanding of both the ecological and socio-political causes and constraints to change. The challenge is to utilize the depth of knowledge available in both the social and ecological literature in effecting this change. Theory can help integrate knowledge across disciplines and is useful in classifying, explaining and predicting the world around us. It has proven its use in a variety of disciplines. For example, fisheries management has improved tremendously by the use of theory to understand how the biology of fish stocks relate to the social dynamics of competing fisherman (Bailey et al., 2010; Tavoni et al., 2012). Fish cooperatives that acknowledge these relationships have demonstrated the capacity to effectively subvert the tragedy of the commons and help fish stocks recover (Leal, 1998). Microbiology is undergoing a similar transdisciplinary revolution (Prosser et al., 2007). New epidemiology models now research the spread of pathogens as a function of both the evolution of microbes and hospital management policies (Grenfell et al., 2004). We now know that over-prescription of antibiotics can lead to the development of disease resistance strains including *Clostridium difficile* (Laxminarayan et al., 2013). Researchers and practitioners now acknowledge that curing these diseases requires careful consultation amongst doctors and patients and may even require the restructuring of entire hospital systems (Drohan et al., 2019). Researchers are also using ecological theories to understand human microbiomes (Costello et al., 2012). Ecological theory on species interactions and community assembly has provided important insights on how human microbiomes differ across populations and what this may mean for human health and disease (Costello et al., 2012). In all of these systems, there are clear social and ecological components that must be managed together to achieve successful outcomes. The potential for theory to also facilitate agroecological transitions is clear.

Critical transition theory can lend tremendous insights into our understanding of agroecological change. The theory is used predominately in the field of ecology and describes sudden changes between two alternative stable states (Scheffer, 2009). These alternatives often represent ecosystem states for example, savannas-forests or eutrophic-oligotrophic lakes (Carpenter et al., 1999; Hirota et al., 2011; Staver et al., 2011). Studies of critical transitions involve evaluating the factors that lock systems in one state and push them toward another state. For example, phosphorus runoff from agriculture into freshwater lakes has been demonstrated experimentally to drive algae blooms characteristic of eutrophic lakes to grow suddenly in otherwise clear, oxygen-rich oligotrophic lakes (Carpenter et al., 1999; Scheffer and Carpenter, 2003). However, reducing runoff does not result in a linear return to the oligotrophic state. Feedback between biological sources and sinks of nutrients can trap the lake in the eutrophic state; in this case, the algae creates an anoxic environment that excludes its predators and competitors from growing (Carpenter et al., 1999). Techniques from critical transition theory can be similarly applied to understanding how agricultural systems can transition from high input to self-sustaining ecosystems.

Given the diversity of agents and drivers of change at play in agricultural systems, complex system theory is also useful. Theories of complex systems provide insight on how patterns emerge from individual behaviors and interactions (Levin, 1992, 1998) For example, the higher-scale pattern and dynamics of transitioning from high input agriculture toward agroecological farming can be understood and predicted through examining how interactions amongst critical agents influence farm management decisions. Here, game theory can be useful. Game theory emphasizes competition amongst decision-makers and has been used to understand the development of social norms, cooperation and non-ideal outcomes (Santos et al., 2018). For example, scholars use game theory to understand how global coordination of climate change mitigation is impeded by the self-serving needs of competing nations, revealing the necessity for local institutions to penalize free-riders and encourage cooperation (Vasconcelos et al., 2013; Pacheco et al., 2014). Theory like this generates predictions that can be of practical value for practitioners and policymakers looking to facilitate agroecological change. It can help define the forces and pathways by and through which agroecological transitions are most likely to occur, as well as portend any unforeseen issues along the way. Utilizing theoretical approaches like this will allow us to organize collective efforts toward food system change and make good use of limited funding and human capital.

Though agroecology holds significant promise of simultaneously improving human welfare and ecosystem function, successfully transitioning from conventional forms of agriculture to agroecology requires a systematic study of the agents and drivers that not only promote transitions to agroecology but can also sustain them into the future. Without theory, our understanding of agroecological transitions is limited to qualitative descriptions of a small number of case studies or specific contexts that are not easily extended to future scenarios and cannot be broadly applied to agroecological transitions, generally. Theory can help weave a common thread through disparate case studies and reveal mechanisms behind observed patterns. Here we review the literature on agroecological transitions with a special focus on theory. We first present a classic theory on agrarian transitions from Marx and Chayanov and then classify the modern socio-ecological literature and case studies on food system change into prominent syndromes of production, agents, barriers, drivers and modes of change that together with the general theory provides a systematic approach for understanding agroecological transitions.

A MATHEMATICAL PERSPECTIVE ON AGROECOLOGICAL TRANSITIONS

The concept of agrarian change has fascinated scholars since Karl Marx's original treatise on capitalism (Marx, 1867). According to Marx, the peasant class was bound to disappear as capitalism progressed, dispossessing peasants and moving them into the proletariat and eventually, bourgeois class. Would peasants go-willingly or resist? That was the agrarian question, a question for which Alexander Chayanov, a Soviet agronomist and economist, proposed a theory of the peasant economy (Chayanov, 1966). Chayanov argued that the peasant class, by being both worker and owner of the farm, was uniquely positioned between the proletariat and bourgeois classes, and as such, not subject to the same rules of capitalist progress and were therefore unlikely to disappear. Chayanov argued that farmers first sought to produce enough food to feed the family. Any work beyond production for subsistence had to strike a balance between the utility and drudgery of that work, in other words, a balance between the needs of their competing proletariat and bourgeois identities. Modern-day agrarian studies continue to address the conflicting identities of farmers and theorize motivations for the simultaneous existence of de and re-peasantization movements (van der Ploeg, 2009; McMichael, 2012). As part of this discourse, scholars delineate farmers and farming styles into syndromes of production, which are simplified here into capitalist and peasant extremes (Altieri, 1983; Vandermeer, 1997; van der Ploeg, 2009; Rosset and Altieri, 2017; Carlisle et al., 2019).

Syndromes of Production

The Capitalist

Since the Green Revolution, agricultural practices have increasingly shifted toward high input, low labor, monoculture production schemes (van Ittersum and Rabbinge, 1997; Caron et al., 2014). These so-called "conventional" systems focus on the production of low-cost, consistent agricultural products with sometimes severe environmental consequences (IAASTD, 2009). For example, the large-scale production of a single crop variety tends to attract similarly large densities of pests and encourages the overuse of chemical fertilizers that can cause eutrophication events in nearby waterways, contribute to climate change and feed weeds (Townsend and Howarth, 2010). Cloning propagation techniques used to create seedless varieties and produce more consistent products also deplete genetic diversity and increase risks to crop disease (Ploetz, 1994). In response, capitalist systems have devised increasingly complex suites of chemical pesticides, fungicides, herbicides and genetically engineered varieties of crops to combat these problems (World Health Organization and United Nations Environment Programme, 1990; Russell, 2001; Tilman, 2001). Though chemical inputs and genetically modified organisms (GMOs) are backed by profitable corporations and provide temporary relief for pest, disease and even climate-change induced problems, these technical solutions are also known to have dramatic consequences on water quality, biodiversity, human health, livelihoods, and ecosystem function (Zhang et al., 2007; Power, 2010).

The Peasant

Though large-scale conventional agricultural systems are the dominant production style for much of the developed world, 92.3% of farms worldwide are small (as defined on a country by country basis but generally less than 2 ha in area) and 70% remain operated by families (GRAIN, 2014; Lowder et al., 2016). Despite this, small-holders control only 24.7% of all agricultural land, while our best current estimates suggest that these farms still provide the majority of food produced for human consumption at the global scale, 53% according to the ETC group and 80% of food in non-industrialized countries (GRAIN, 2014; ETC Group, 2017). Note that low-input, small-scale and family-run are insufficient terms when used in isolation for describing the peasant syndrome in the agroecology transition literature. This is because many family farms are large-scale input intensive operations, while many small farmers are similarly high input users (Graeub et al., 2016; Carlson et al., 2017). Family farms have been separated into at least three groups: (1) wealthy farmers invested heavily in markets, (2) those with reasonable assets that do not qualify for social safety nets and access to credit or collective action, and (3) land-poor farmers that engage heavily in non-market activities and rely on subsistence farming (Graeub et al., 2016). In this paper we refer to small-scale, low-input family farms engaged heavily in non-market activities as comprising the peasant syndrome. The capitalist syndrome is defined as large-scale high-input farms relying primarily on market capital as their livelihood, whether family operated or not. Small-scale, low-input family farms are thought to espouse the characteristics of the peasant class by producing food for subsistence, relying on family labor and balancing commitments to markets with family needs (Chayanov, 1966; Otsuka et al., 2016). This syndrome of production is characterized by operation with few external inputs, relying primarily on ecological knowledge and processes to support the farm often in the form of traditional indigenous techniques (Altieri, 2009; Altieri et al., 2012). These may include the use of nitrogen fixers and composting to support soil quality and plant nutrition and the support or deployment of natural enemies and biological control agents to provide pest control services (Clawson, 1985; Denevan, 1995; Altieri, 2018). Smaller low-input farms also tend to optimize space, light and nutrient requirements by employing higher rates of family labor and a greater diversity of crops to take advantage of microhabitats on the farm (Lin, 2007; Altieri, 2009; Larson et al., 2012). Intensively managed small-tracts of land appear more productive than larger farms owing to both the behavioral and bio-physical properties of managing smaller plots where labor and resources can be better distributed (Bevis and Barrett, 2020). Small, low-input family farms are arguably more effective at reducing food insecurity and protecting ecosystem services by producing first for subsistence of the family rather than for income through external markets and also diversifying crop production to reduce potential market risks or unforeseen losses from environmental perturbations (Altieri et al., 2012; Larson et al., 2012; van der Ploeg, 2014; Graeub et al., 2016). Though many claim that low input agroecological techniques have productivity ceilings that are necessarily below high-input technological alternatives (Wilbois and Schmidt, 2019), some scholars retort that these limits are due primarily to social rather than technical factors, since for example, some subsistence farmers do not produce beyond what is required for subsistence, peasants often operate on marginal lands and agroecology receives less funding for technical innovations (Carter, 1984; Altieri et al., 2012; van der Ploeg, 2014; DeLonge et al., 2016).

Our description of the peasant syndrome does not extend to wage-reliant landless agricultural workers and the urban poor. Access and control of land is a key component of the peasant state that some landless people aspire to, while others do or cannot (van der Ploeg, 2009; McMichael, 2012). Although the existence of simultaneous re and de-peasantization movements are important to note, these are not the primary focus of this review. The push for development and increasingly difficult social, economic and environmental conditions can lead to land dispossession for peasants and/or transitions to farm wage labor (Robles, 2001; Foster and McChesney, 2017). This is often accompanied by seasonal or permanent migration, most commonly by the head of household or children of the family, from rural to urban sites when rural livelihoods prove too difficult to sustain (McMichael, 2012). From a theoretical perspective, transitions to rural farm wage labor and into the urban poor class could be conceived of as instability in the peasant syndrome rather than part of the peasant syndrome itself, a concept we will address later on.

Farms in Between

In reality, capitalist and peasant syndromes represent extremes on a continuous scale of farm management. Many farms vary in the extent to which ecology and sustainability are incorporated in their design, including those that belong to the other alternative agriculture paradigms outlined in the introduction. As previously mentioned, family farms vary in their spatial scale, input usage and dependence on capitalist markets for survival although family labor, heritage and legacy remain key considerations in the management of most family farms. Some farms may substitute technological inputs with those derived from nature, e.g., substituting nitrogen fixers for fertilizers and biological control agents for pesticides (Tittonell, 2014). These methods can be employed to achieve "sustainability" goals without addressing the broader social inequities of the food system in which a farm is embedded. Though there is some variance surrounding the meaning of the umbrella term "agroecology," the dominant definition in the literature explicitly incorporates human society and politics into the ecology of the farm, requiring sustainability from these perspectives as well (Gliessman, 2014; Rosset and Altieri, 2017). For example, rather than focus on supplying food security, agroecology often requires food sovereignty- which is defined not only as the access to and production of sufficient calories to feed a population (the definition of food security), but also the right for farmers to produce, and consumers to access, culturally-appropriate foods using ecologically sustainable methods while securing respectable and healthy farmer livelihoods. Other food movements may include some or all of the ecological lessons of agroecology but vary substantially in the degrees to which the social tenets are adopted (Allen and Sachs, 1991). This has led many scholars to criticize so-called "green-washed" food movements that intentionally avoid addressing socio-political issues or considering management effects at the global scale, while making sometimes marginal steps to improve their environmental footprint (Rosset and Martínez-Torres, 2012; Chappell et al., 2016).

The grassroots organization, La Via Campesina, organizes the largest global peasant-led movement that "defends peasant agriculture for food sovereignty as a way to promote social justice and dignity and strongly opposes corporate driven agriculture that destroys social relations and nature" (Altieri and Toledo, 2011; Via Campesina, 2019). This text from the La Via Campesina website exemplifies the embodiment of two distinct syndromes of production in agriculture, a self-proclaimed peasant agriculture that is juxtaposed with a corporate-driven alternative that echoes the same agrarian question first proposed by Marx and Chayanov (Chayanov, 1966).

Syndromes as Steady States

From a mathematical perspective, these syndromes of production can be interpreted as alternative states, which are sets of equilibria in a dynamical system (Vandermeer, 1997; Vandermeer and Perfecto, 2012). Should these syndromes be stable, we would expect that small deviations away from the characteristics of a prototypical state should result in returns to the original characteristics. In order to represent an equilibrium, the characteristics of each farming syndrome should be consistent enough to become distinctly recognizable. Today's agrarian studies overwhelmingly present capitalist and peasant farmers as two alternative syndromes of production. We conducted a targeted search on the Web of Science for papers including the terms "hysteresis + agriculture + transition," "agroecology + hysteresis," "syndromes of production," "agroecology + resilience," and "agroecological + transition" in order to focus on papers that could lend mathematical perspectives on food system change. From this review of the literature we found a total of 37 papers (**Supplementary Table 1**), 14 of which described characteristics of agricultural production that we interpreted as syndromes (**Table 1**). Based on our literature review, peasant and capitalist alternatives do appear to embody a set of basic characteristics that could be conceived of as stable states. By conceived of, we mean that peasant and capitalist syndromes are commonly described in the agroecological transition literature by a set of characteristics aforementioned, which are recognizable and reasonably consistent. We argue that this consistency is the first but, are careful to concede, is not the only requirement for dynamic stability, a matter we will address later on. At the same time, peasant agriculture has been juxtaposed against capitalist farming since time immemorial, supporting the assertion that these two syndromes could also represent the alternative stable states of critical transition theory (Marx, 1867; Chayanov, 1966; Andow and Hidaka, 1989; Vandermeer and Perfecto, 2012).

Agents of Food System Change

In our review of the transition literature we found three general frameworks that have been primarily used by scholars to analyze food systems change: a socio-ecological framework, a socio-technological framework and a framework that investigates social norms and networks. A detailed assessment of these three frameworks reveals the key agents involved in effecting food systems change. Overlap in agents across the frameworks allows us to visualize the complexity of the food system and examine its operation at many scales (**Table 1**, **Figure 1**).

The socio-ecological framework focuses on farmer to farm interactions. It is used to investigate how farm management decisions affect food production and the environment, and how the environment then feedbacks via natural resource fluctuations to influence future farming practices. Key concepts explored in this framework include the synergies and tradeoffs of ecosystem services (**Figure 1**). Soil management of rangelands provides a good example of this framework. Overgrazing by cattle can lead to soil erosion and the loss of future productivity (Schlesinger et al., 1990; Milchunas and Lauenroth, 1993). Soil conservation techniques including rotational grazing and agroforestry can build resilience in soils and promote cattle health but often supports smaller herds than conventional, full-sun fields (Jacobo et al., 2006; Dollinger and Jose, 2018). One suggested solution is to diversify farmer livelihoods so that trees can provide alternative incomes in the form of timber and fruit, but this solution requires sufficient access to markets, processing infrastructure and consumer support (Schroth and Ruf, 2014). Key agents and factors in the socio-ecological framework include the farm, farmer, markets, consumers, natural resources and environmental conditions including the effects of climate change (**Table 1**, **Figure 1**).

The socio-technological framework explores the technological and structural lock-ins that prevent shifts to agroecology. Currently, most of our understanding of this framework comes from the social sciences (**Table 1**). This framework investigates how advances in technology are influenced by institutional policies and investments. These technologies directly affect farming practices, which feedback to influence market conditions, farmer revenues and dependence on the development of future technologies (Arthur, 1989; Russell, 2001). Genetically modified crops designed for herbicide resistance provides a key example. Round-up ready corn and soy are able to withstand herbicide applications that non-GMO corn are unable to tolerate (Jordan, 2002). However, new GMOs and herbicides constantly need to be developed in order to keep up with the evolution of resistance by weed species (Mikkelsen et al., 1996; Powles et al., 1996; Rissler et al., 1996; Russell, 2001; Jordan, 2002). Also, GMOs have triggered intense debate amongst consumers, markets and farmers as institutions develop labeling and regulation practices for the technology that in turn impact farm management practices (Caswell, 2000). The socio-technological framework includes technology, institutions, markets, consumers and the farmer/farm as key agents of change or resistance (**Table 1**, **Figure 1**).

A third framework describes the effects of social norms and networks on agricultural change. This framework is useful in understanding how market structure, for example, a central monocentric trading network vs. a polycentric locally based network, affects farmer decisions to adopt alternative farming practices, and concurrently, how farmer decisions affect the evolution of trading networks. Elinor Ostrom's thesis on managing the commons provides a key example of this framework (Ostrom, 1990). Ostrom conducted a thorough analysis of small, African pastoral communities whose soils experienced severe degradation when colonists fragmented once continuous tracts of pastureland into smaller, private lots. Despite the imposition of a monocentric trading network that was intended to secure financial rights to agricultural products, pastoralists maintained local relationships with one another, creating a new polycentric network through mutual trust where people traded access to land, restoring the communal pastureland and soil health (Ostrom, 1990). This framework is also useful in providing insights on how agroecological transitions can be facilitated through changes in social norms and collective action. Here, game theory is particularly useful in understanding how information propagates among farmers and how coalitions between agents can form and be sustained. In this framework, key agents of change include farmers, farm, markets and consumers (**Table 1**, **Figure 1**).

An examination of the links between agents within each of the aforementioned frameworks provides a sketch of the overall network structure of food systems and reveals its common

TABLE 1 | Summary of reviewed papers.

Theoretical concept	Disciplines	#	Papers	Study locations	CF
Syndromes of production (what are the agricultural states?)	Ecology/Natural Science	10	Vandermeer, 1997; Kremen et al., 2012; Vandermeer and Perfecto, 2012, 2017, 2019; Wang et al., 2012; Jacobi et al., 2015; Ong and Vandermeer, 2018; Perfecto et al., 2019; Valencia Mestre et al., 2019	Mexico, Brazil, Bolivia, Neotropics	SE, NN
	Social Science	12	Vandermeer, 1997; Codjoe, 2006; Rosset et al., 2011; Kremen et al., 2012; Vandermeer and Perfecto, 2012; Jacobi et al., 2015; Levidow, 2015; DeLonge et al., 2016; Schipanski et al., 2016; Cayre et al., 2018; Perfecto et al., 2019; Valencia Mestre et al., 2019	Neotropics, Brazil, United States, Ghana, France, Mexico, Bolivia, Europe, Cuba	SE, NN
	Physics/ Mathematics	6	Vandermeer, 1997; Vandermeer and Perfecto, 2012, 2017, 2019; Wang et al., 2012; Ong and Vandermeer, 2018	Mexico, Brazil	SE
Agents (who are the change makers?)	Ecology/ Natural Science	14	Vandermeer, 1997; Kremen et al., 2012; Vandermeer and Perfecto, 2012, 2017, 2019; Wang et al., 2012; Tittonell, 2014; Babin, 2015; Blesh and Wittman, 2015; Jacobi et al., 2015; Dendoncker et al., 2018; Ong and Vandermeer, 2018; Perfecto et al., 2019; Valencia Mestre et al., 2019	Mexico, Neotropics, Brazil, Costa Rica, Kenya, Cameron, East Africa, Bolivia	SE, NN
	Social Science	32	Vandermeer, 1997; Codjoe, 2006; Altieri, 2009; Altieri and Toledo, 2011; Rosset et al., 2011; Altieri and Nicholls, 2012; Fares et al., 2012; Kremen et al., 2012; Rosset and Martínez-Torres, 2012; Vandermeer and Perfecto, 2012; Petersen et al., 2013; Blesh and Wolf, 2014; Duru et al., 2014, 2015; Levidow et al., 2014; Tittonell, 2014; Babin, 2015; Blesh and Wittman, 2015; Castella and Kibler, 2015; Jacobi et al., 2015; DeLonge et al., 2016; Meek, 2016; Rodríguez, 2016; Schipanski et al., 2016; Beudou et al., 2017; Moore, 2017; Cayre et al., 2018; Dendoncker et al., 2018; Nicholls and Altieri, 2018; Parodi, 2018; Perfecto et al., 2019; Valencia Mestre et al., 2019	Neotropics, Brazil, United States, France, Ghana, Southeast Asia, Haiti, Argentina, Costa Rica, Mexico, Cuba, Kenya, Cameron, East Africa, Latin America, Bolivia	SE, ST, NN
	Physics/ Mathematics	7	Vandermeer, 1997; Vandermeer and Perfecto, 2012, 2017, 2019; Wang et al., 2012; Tittonell, 2014; Ong and Vandermeer, 2018	Mexico, Brazil, Kenya, Cameron, East Africa	SE, NN
Drivers (what factors drive change?)	Ecology/Natural Science	14	Vandermeer, 1997; Kremen et al., 2012; Vandermeer and Perfecto, 2012, 2017, 2019; Wang et al., 2012; Tittonell, 2014; Babin, 2015; Blesh and Wittman, 2015; Jacobi et al., 2015; Dendoncker et al., 2018; Ong and Vandermeer, 2018; Perfecto et al., 2019; Valencia Mestre et al., 2019	Mexico, Neotropics, Brazil, Costa Rica, Kenya, Cameron, East Africa, Bolivia	SE, NN
	Social Science	32	Vandermeer, 1997; Codjoe, 2006; Altieri, 2009; Altieri and Toledo, 2011; Rosset et al., 2011; Altieri and Nicholls, 2012; Fares et al., 2012; Kremen et al., 2012; Rosset and Martínez-Torres, 2012; Vandermeer and Perfecto, 2012; Petersen et al., 2013; Blesh and Wolf, 2014; Duru et al., 2014, 2015; Levidow et al., 2014; Tittonell, 2014; Babin, 2015; Blesh and Wittman, 2015; Castella and Kibler, 2015; Jacobi et al., 2015; DeLonge et al., 2016; Meek, 2016; Rodríguez, 2016; Schipanski et al., 2016; Beudou et al., 2017; Moore, 2017; Cayre et al., 2018; Dendoncker et al., 2018; Nicholls and Altieri, 2018; Parodi, 2018; Perfecto et al., 2019; Valencia Mestre et al., 2019	Neotropics, Brazil, United States, France, Ghana, Southeast Asia, Haiti, Costa Rica, Mexico, Cuba, Kenya, Cameron, East Africa, Latin America, Bolivia	SE, ST, NN
	Physics/ Mathematics	7	Vandermeer, 1997; Vandermeer and Perfecto, 2012, 2017, 2019; Wang et al., 2012; Tittonell, 2014; Ong and Vandermeer, 2018	Mexico, Brazil, Kenya, Cameron, East Africa	SE, NN

(Continued)

TABLE 1 | Continued

Theoretical concept	Disciplines	#	Papers	Study locations	CF
Inhibitors (what factors inhibit change?)	Ecology/Natural Science	11	Vandermeer, 1997; Kremen et al., 2012; Vandermeer and Perfecto, 2012, 2017, 2019; Wang et al., 2012; Tittonell, 2014; Dendoncker et al., 2018; Ong and Vandermeer, 2018; Perfecto et al., 2019; Valencia Mestre et al., 2019	Mexico, Neotropics, Brazil, Kenya, Cameron, East Africa	SE, NN
	Social Science	24	Vandermeer, 1997; Altieri, 2009; Altieri and Toledo, 2011; Altieri and Nicholls, 2012; Fares et al., 2012; Kremen et al., 2012; Rosset and Martínez-Torres, 2012; Vandermeer and Perfecto, 2012; Petersen et al., 2013; Duru et al., 2014, 2015; Levidow et al., 2014; Tittonell, 2014; Castella and Kibler, 2015; DeLonge et al., 2016; Meek, 2016; Rodríguez, 2016; Schipanski et al., 2016; Beudou et al., 2017; Moore, 2017; Dendoncker et al., 2018; Parodi, 2018; Perfecto et al., 2019; Valencia Mestre et al., 2019	Neotropics, Brazil, United States, France, Southeast Asia, Haiti, Argentina, Mexico, Cuba, Kenya, Cameron, East Africa, Latin America	SE, ST, NN
	Physics/ Mathematics	7	Vandermeer, 1997; Vandermeer and Perfecto, 2012, 2017, 2019; Wang et al., 2012; Tittonell, 2014; Ong and Vandermeer, 2018	Mexico, Brazil, Kenya, Cameron, East Africa	SE, NN
Modes of change (how are changes experienced?)	Ecology/Natural Science	12	Vandermeer, 1997; Kremen et al., 2012; Vandermeer and Perfecto, 2012, 2017, 2019; Wang et al., 2012; Tittonell, 2014; Babin, 2015; Blesh and Wittman, 2015; Ong and Vandermeer, 2018; Perfecto et al., 2019; Valencia Mestre et al., 2019	Mexico, Neotropics, Brazil, Costa Rica, Kenya, Cameron, East Africa	SE, NN
	Social Science	17	Vandermeer, 1997; Altieri and Toledo, 2011; Rosset et al., 2011; Kremen et al., 2012; Rosset and Martínez-Torres, 2012; Vandermeer and Perfecto, 2012; Petersen et al., 2013; Tittonell, 2014; Babin, 2015; Blesh and Wittman, 2015; Castella and Kibler, 2015; Meek, 2016; Rodríguez, 2016; Nicholls and Altieri, 2018; Parodi, 2018; Perfecto et al., 2019; Valencia Mestre et al., 2019	Neotropics, Brazil, Southeast Asia, Argentina, Costa Rica, Mexico, Cuba, Kenya, Cameron, East Africa, Latin America	SE, ST, NN
	Physics/ Mathematics	7	Vandermeer, 1997; Vandermeer and Perfecto, 2012, 2017, 2019; Wang et al., 2012; Tittonell, 2014; Ong and Vandermeer, 2018	Mexico, Brazil, Kenya, Cameron, East Africa	SE, NN

We classify papers into the five key theoretical concepts, three disciplines. We summarize the number of papers in each category (#) and identify the study locations (including countries and regions) and conceptual framework (CF) applicable to the studies. The frameworks are socio-ecological framework (SE), socio-technological framework (ST), and norms-and-networks framework (NN).

links. We begin with three key agents that are shared across these frameworks: farmers, consumers, and markets (**Figure 1**). These three agents directly influence one another through the production, consumption and sale of food products. The structure and composition of these interactions are described by the social norms and networks framework and represent the social components of both the socio-ecological and socio-technological frameworks (**Figure 1**). From this diagram we can see that food systems are complex adaptive systems composed of many interacting decision-makers. Farm management decisions ultimately influence the rates and directions of food system change but can occur through direct or indirect pathways (**Figure 1**). Transitions can be assessed from the perspective of any single agent or multiple agents at a time and at various scales ranging from a single farm to the global food system. The choice of agents and scale largely determine what patterns and dynamics of food system change we observe. This dependency requires careful attention toward understanding the mechanism behind patterns of food system change and acknowledgment that patterns do not necessarily translate across scales and units of analysis. With this in mind, we turn to specific case studies of change described in the literature.

Case Studies of Change

From Peasant to Capitalist

Though agroecological transitions represent movement from capitalist to peasant modes of production (Rosset and Altieri, 2017), these transitions are incomplete without first understanding transitions from peasant to capitalist syndromes. The green revolution represents an important widespread shift into the capitalist syndrome. Farmers in the U.S. maintained robust livelihoods for much of their history, supported by government policies that managed supplies and controlled crop prices to avoid market surpluses. However, these policies were dismantled when large corporations started lobbying congress in the 1950s. Companies lobbied for government subsidies on crops, which encouraged farmers to produce more food but did not ensure that they would make profits. Farmers were able to

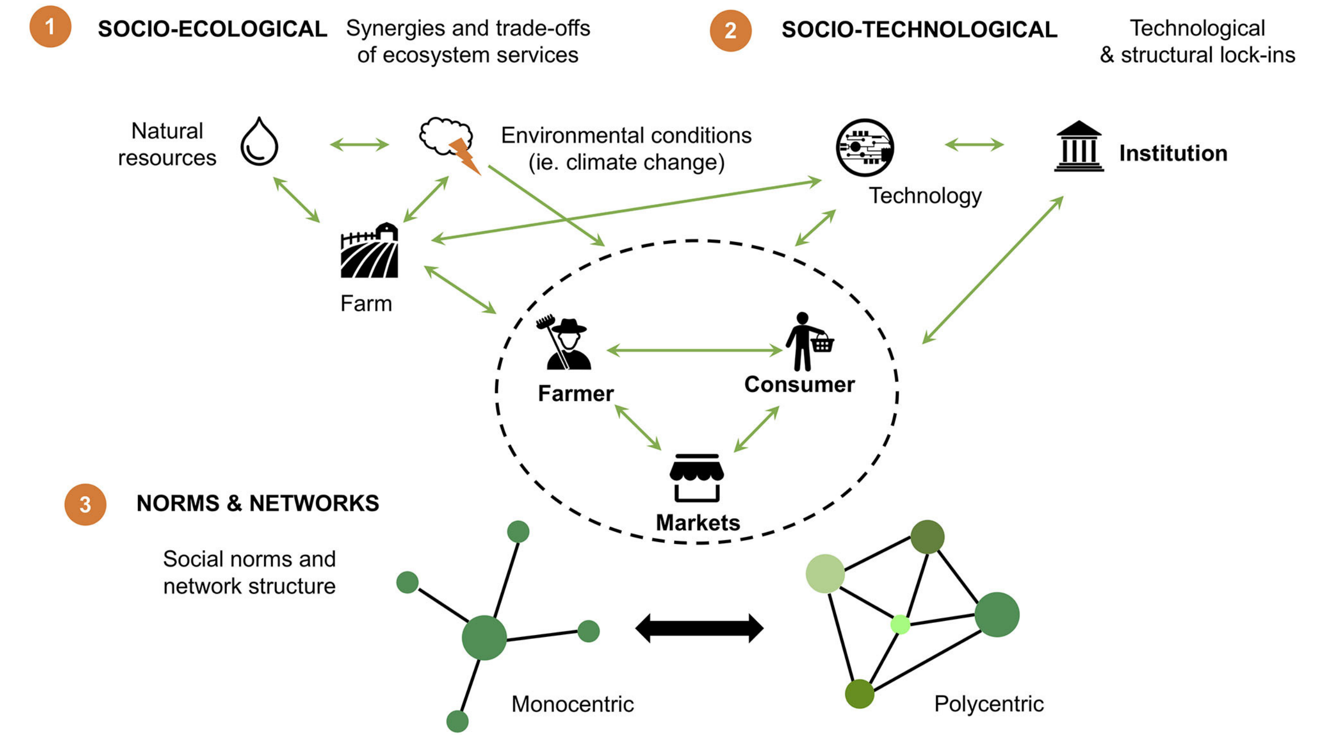

FIGURE 1 | Conceptual diagram of key agents and interactions in the transformation of food systems. Key decision-making agents include farmers, consumers, markets and institutions (bolded). We identify three main frameworks used to study agroecological transitions in the literature: (1) socio-ecological, (2) socio-technological, and (3) social norms and networks frameworks. The third framework describes the structure of interactions of the first two frameworks. The three frameworks are also connected through analyses of interactions amongst farmers, consumers and markets (dashed circle). Their behaviors influence one another and spur changes in both the environmental sustainability or degradation and technological development of farming practices. We highlight three main areas of research on agroecological transitions within these frameworks: synergies and trade-offs in ecosystem services, technological and structural lock-ins, and social norms and network structure.

fulfill the demand for larger yields when synthetic fertilizers, first invented in the early 1900s by Fritz Haber and later industrialized by Carl Bosch (Erisman et al., 2008), were popularized by Norman Borlaug in the 1960s (Patel, 2013). Large-scale changes in agricultural production in the U.S. were spurred by the combination of synthetic fertilizers and high-yield crop varieties, bringing about a green revolution that was then emulated by developing countries across the globe. Excess production of corn and soy created new markets for processed food products that had the result of homogenizing diets and creating dependencies on cheap food (Schipanski et al., 2016). These changes increased agricultural production, but also increased environmental degradation and social inequities (Griffin, 1974). Though agricultural yields increased dramatically, farmer livelihoods saw little improvement. Government subsidies largely favored food processors and distributors who benefited from record-low market prices (Carlisle et al., 2019), while small farmers became increasingly marginalized as profits declined and farming knowledge was replaced with technology. Today, the capitalist farming syndrome relies heavily on un-skilled repetitive tasks and large machines that save labor. Though industrial farming is still a very complex job requiring a suite of agronomic, economic and technical skills, shifts in technology reduce the number of farmers required to work increasingly larger parcels of land (Gale, 1996) and changes in economic policy have made farming an unwelcoming profession in many countries where capitalist farming dominates including the U.S. and India, where farmer age and suicide rates are at all-time highs (Lobao and Meyer, 2001; Gale, 2003; Merriott, 2016; Carlisle et al., 2019).

From Capitalist to Peasant

There are some key examples in the literature where agriculture has successfully reverted back from capitalist to peasant modes of production. The most famous example is Cuba's agroecological transition following the collapse of the socialist bloc and the institution of U.S. trade embargoes. Following these events, many Cubans were forced to grow their own food when access to imported foods and agrochemicals were suddenly limited and widespread famine occurred (Nicholls and Altieri, 2018). As a result, the country adopted the campesino a campesino (CAC), or farmer-to-farmer, methodology promoted by the National Association of Small Farmers (ANAP) to transition the previously cash crop dominant national agriculture system (sugarcane and tobacco exports) into a diversified farming system capable of nourishing its trade embargoed citizens (Nicholls and Altieri, 2018). The movement has since greatly increased the number of peasant families and their contribution to domestic food production (70%) (Rosset et al., 2011).

A similar transition occurred in Costa Rica when an international coffee agreement that set target coffee prices and managed supplies to maintain a stable international market collapsed, causing a monetary crisis that encouraged farmers to reduce chemical inputs and adopt agroecological practices (Babin, 2015). Costa Rican coffee farmers were faced with over $1,100 per ha in debt following the collapse of the agreement (Varangis et al., 2003). In 1999, the "sustainable group" (SG) of 61 coffee farmers in Agua Buena organized a movement to use shade trees and drastically reduce the use of expensive external chemical inputs. SG later joined the free government program Caficultura Sostenible en Pequenas Fincas (Sustainable Coffee Production in Small Farms), which provided structure, leadership, training and resources to guide transitions to alternative agroecology-based coffee production.

Many countries have transition movements led by grassroots organizations. In Brazil, O Movimento dos Trabalhadores Rurais Sem Terra (the MST, or Landless Rural Workers Movement), one of the largest members of La Via Campesina, was formed in the mid-1980s in order to pressure the government to fulfill its constitutional commitment of land reform by providing land access to peasants. Over 6,000 landless families occupied unproductive land in the country and converted it to agroecological farms (Robles, 2001; Blesh and Wittman, 2015). In Haiti, the Peasants' Movement of Papaye (MPP) was formed against the market liberalization of Duvalier's dictatorship in 1973 that primarily supported agribusiness and foreign investments. MPP organized local peasants, trained them in agroecology and negotiated environmental and social change through collective political action (Moore, 2017). In Bolivia, El Ceibo, a federation of local cooperatives, provided certification for organic cocoa production. The federation also provided supplies of shade tree seedlings and technical assistance to encourage farmers to shift from monocultures to diversified agroforestry systems (Jacobi et al., 2015). The Land Workers Union (UTT) cooperative has organized many family farmers, mostly of Bolivian origin, to spread agroecological farming practices and facilitate an agroecological transition in the horticultural belt outside of Buenos Aires. This region is an important agricultural region in Argentina and has, for decades, relied on external inputs such as fertilizers and pesticides for conventional agriculture. UTT designed a "System for the Healthy Production of Healthy Vegetables" to aid new farmers in implementing agroecological alternatives to the conventional standard. Farmers who participate in the system have access to training sessions on agroecological techniques and diversified markets that cut out intermediaries and create short food supply chains by directly selling to consumers (Le Velly and Dubuisson-Quellier, 2008).

Barriers to Agroecological Transitions

Transitions back to the peasant syndrome present many challenges that seem to indicate a strong stability in the capitalist syndrome. We review the literature on barriers to agroecological transitions and summarize the findings below (**Table 1**).

Many of our case studies of agroecological transitions involve new farmers, yet new farmers face many challenges. New farmers must have access to land with adequate natural resources (e.g., water). They must compete for land with other land use types such as housing, city infrastructure and conservation easements (Hamilton, 2010; Ostrom et al., 2010). Land-use policy, economic status and race may also determine whether a new farmer can establish roots in a given community (Barraclough, 2009). Our current food system restricts land ownership, which disproportionately affects minority groups. Though minority groups often comprise a majority of farm workforces, they also often own much less land (Gilbert et al., 2002; Mandell, 2009). When minority farmers are able to secure land, they face additional challenges. For example, the U.S. has a long history of wresting away African American land that was secured following the Civil War's promise of forty acres and a mule (Reid and Bennett, 2012). A series of both direct and indirect policies targeting black landowners is thought responsible for much of the Great Migration in the 1900s. As a result, black-owned farms have decreased markedly in the U.S. from its height at 14% in 1920 to <1% today (Daniel, 2013). Women are also marginalized in agriculture, representing as little as 2% of global landowners despite comprising the dominant agricultural workforce with the caveat that this exact percentage varies from report to report and country to country owing to a lack of data. However, rampant gender discrimination in regards to farm management rights, access to credit and general cultural limitations to "women-work" are largely undisputed (Meares, 1997; Saugeres, 2002; GRAIN, 2014).

Secondly, established capitalist farmers must have adequate financial capital in order to transition from conventional practices to agroecological alternatives (Schiller, 2017). Specific financial costs include equipment, wages, processing facilities and the time investment necessary for production to adapt to a new management regime (Schiller, 2017). However, the outcomes of adopting new farming practices are unknown and create financial risks that some farmers are unwilling or incapable of tolerating, presenting a third, related barrier to transitions. Farmers tend to be risk-averse, especially with increasing climate and food price volatility (Development OECD, 2009, 2011). Our current financing and insurance regimes are not well-suited for facilitating agroecological transitions. Much of the initial investments required, for example, in building soil health, may not yield benefits for years. Short-term loans available to farmers cannot buffer farmers from long-term risks associated with shifting into agroecology (Menapace et al., 2013; Belasco, 2017; Woodard and Verteramo-Chiu, 2017).

Fourthly, adequate social capital is required. In order to successfully transition from the capitalist to peasant syndrome, farmers require the necessary labor to conduct the work as well as the social support from other farmers, consumers, community members and the local government (Carlisle et al., 2019). Peasant farms often have high-labor demands (Carlisle et al., 2019). In the absence of sufficient family members to conduct the work, peasant farmers need to secure a stable labor force and pay for increased labor cost to meet the justice goals of food sovereignty in agroecology (Carlisle et al., 2019). In the current global system, fair pay for farmworkers can raise food prices, requiring consumers to bear some of the cost, another important social capital required for effective change (Bacon, 2005; De Pelsmacker et al., 2005).

Lastly, agroecology requires local natural system knowledge. Farmers must develop a place-based understanding of their farm that needs to be accumulated through time. This knowledge is necessary for establishing an ecologically and socially resilient food system that can effectively serve the local environment and people. Local knowledge is traditionally passed on through generations, but capitalist farming homogenizes landscapes and obviates local knowledge. The average age of farmers continues to grow as new generations move on to more promising careers (Fairweather and Mulet-Marquis, 2009; Fried and Tauer, 2016). As crucial social networks deteriorate, local knowledge is lost, creating additional barriers for those seeking to transition to agroecology.

Drivers of Change

Despite these challenges, various social factors are implicated in past and expected to help catalyze future transitions from capitalist to peasant syndromes. For example, increasing land access, tenure and providing financing and insurance policies to new farmers can buffer the risks associated with starting a new farm or transitioning from conventional to agroecological farming. Creating spaces for farmers to consult each other and exchange experiences can help catalyze transitions by facilitating the generation and sharing of local agroecological knowledge. Social theory suggests that both horizontal (farmer-to-farmer) and vertical (across institutions) transmission of knowledge is necessary for spurring effective food systems change (Rosset and Martínez-Torres, 2012; Rosset and Altieri, 2017; Carlisle et al., 2019). Loss of local knowledge can be regained through farmer-to-famer (campesino-a-campesino) discourse and collaborations between scientists and farmers. Co-creation of knowledge, rather than unidirectional transfers from scientists to farmers are key to effecting lasting change (Levidow et al., 2014). Both of these methods have successfully aided agroecological transitions in Cuba (Rosset et al., 2011; Rodríguez, 2016). In the U.S., scientist-farmer collaboration is generally spearheaded by land grant institutions, whose missions explicitly include farmer extension programs (Comer et al., 2006). In addition, many countries have "light-house" gardens that offer real-life examples of successful agroecological farms that others can mimic (Nicholls and Altieri, 2018). La Via Campesina uses all of these methods to encourage broad adoption of the "peasant-way of life" (Altieri and Toledo, 2011). The grassroots movement has made marked progress, growing from a predominantly Latin-American movement in 1993 to now including 182 member groups across 81 countries.

Promoting social justice and equity may also help drive transitions toward agroecology. Social justice and equity improve access to resources for many and encourages innovation, which together improve the capacity of food systems to withstand and adapt to environmental disturbances (Chappell and LaValle, 2011). By reducing marginalization and inequality in our current food system, more actors are able to engage in the improvement of the system and can better facilitate a transition toward greater sustainability (Ensor et al., 2015). Decentralizing food distribution networks can also aid transitions toward agroecology. The globalized food system separates consumers from farmers and as a consequence, people from nature, hiding externalities such as the pollution in marginalized communities near industrial farms and farm worker exploitation (Garcia, 2007; Jacques et al., 2012). In contrast, regional food systems encourage local investment as neighbors seek to support each other and steward shared environments (Migliore et al., 2014). Strong local connections foster a social embeddedness that favors the locally oriented, small-scale and environmentally friendly practices that agroecology espouses.

Finally, environmental changes may also trigger transitions in food systems. Due to a lack of crop diversity, conventional farms are less resilient to shifting environmental conditions. The increasing frequency of extreme weather events threatens monoculture production schemes and may incentivize farmers to adopt new agroecological practices (Altieri, 1999; Chappell and LaValle, 2011). For example, planting a greater diversity of crops may ensure that more crops will survive to market in a variable climate. Environmental degradation may also impact market conditions by affecting consumer demands (**Figure 1**). Increasing environmental awareness in consumers has created a preference for locally sourced low footprint food, incentivizing farmers to comply with new market demands (Tregear et al., 1994; Yussefi-Menzler, 2010).

Transitions to Other Alternatives

In this paper we focus primarily on the agroecological transition literature, which is limited based on our search terms to 37 papers at this time (**Supplementary Table 1**). To make sure we did not miss important papers or insights, we expanded our review to examine how the agroecological transition literature compared to the literature on agricultural transitions, more broadly. Specifically, we searched for "agri-ecology + transition" (0 results), "agriecology + transition" (0 results), "restorative + transition" (1 result, 1 relevant), "regenerative farming + transition" (568 results, first 50 reviewed, 6 relevant), "organic farming + transition" (484 results, first 50 reviewed, 7 relevant), "sustainable farming + transition" (568 results, first 50 reviewed, 14 relevant), and "climate smart agriculture + transition" (16 results, 7 relevant) on Web of Science. We examined only the first 50 of each search when there were more than 50 papers. Of these 50, papers were included in our review if they pertained to agricultural transitions and were peer-reviewed articles. Two of these papers described transitions to agroecology and were added to our original list to make 39 (**Supplementary Tables 1, 2**).

We used "agriecology" and its derivative term to include papers in other regions who may prefer this term and find more papers from mathematics and physics, but surprisingly, no papers using "agriecology" in combination with "transition" or "hysteresis" were found. Similarly, when we added "hysteresis" in place of "transition" to the farming adjectives listed above, no papers were found except for combinations with "organic." This search revealed 9 papers, only 2 of which actually described agricultural transitions, which we included (**Table 2**) (Musshoff and Hirschauer, 2008; Riley, 2016). We conclude that the lack of

TABLE 2 | Summary of reviewed papers for transitions to alternative agricultures.

Theoretical concept	Disciplines	#	Papers	Study locations	CF
Syndromes of production (what are the agricultural states?)	Ecology/Natural Science	0			
	Social Science	7	Guthman, 1998; Bouahom et al., 2004; Pearson, 2007; DeLonge et al., 2016; Liu and Liu, 2016; Rosenzweig et al., 2019; Swagemakers et al., 2019	Europe, United States, Laos, China	SE,ST,NN
	Physics/ Mathematics	0			
Agents (who are the change makers?)	Ecology/ Natural Science	0			
	Social Science	30	(Hill and MacRae, 1992; Meares, 1997; Peter et al., 2000; Saugeres, 2002; Zaal and Oostendorp, 2002; Carolan, 2005; González and Nigh, 2005; Hall and Mogyorody, 2007; Pearson, 2007; Musshoff and Hirschauer, 2008; Cranfield et al., 2010; Lamine, 2011; Marini et al., 2011; Sutherland et al., 2012; Bhandari, 2013; Chantre and Cardona, 2014; Patil et al., 2014; Calo and De Master, 2016; Descheemaeker et al., 2016; Liu and Liu, 2016; Long et al., 2016; Riley, 2016; Salvini et al., 2016; Šumane et al., 2018; Chieco et al., 2019; Osuna et al., 2019; Rosenzweig et al., 2019; Schaffer et al., 2019; Swagemakers et al., 2019; Tankha et al., 2020	Europe, United States, Sweden, Nepal, France, Cuba, China, Kenya, Canada,, Italy, Mexico, India, Brazil, sub-saharan Africa, United Kingdom, Germany and Austria	SE,ST,NN
	Physics/ Mathematics	1	Musshoff and Hirschauer, 2008	Germany and Austria	ST
Drivers (what factors drive change?)	Ecology/Natural Science	0			
	Social Science	32	Hill and MacRae, 1992; Meares, 1997; Guthman, 1998; Peter et al., 2000; Saugeres, 2002; Bouahom et al., 2004; Carolan, 2005; González and Nigh, 2005; Hall and Mogyorody, 2007; Pearson, 2007; Musshoff and Hirschauer, 2008; Cranfield et al., 2010; Lamine, 2011; Marini et al., 2011; Sutherland et al., 2012; Bhandari, 2013; Blesh and Wolf, 2014; Chantre and Cardona, 2014; Patil et al., 2014; Thornton and Herrero, 2015; Calo and De Master, 2016; DeLonge et al., 2016; Descheemaeker et al., 2016; Long et al., 2016, 2019; Riley, 2016; Šumane et al., 2018; Gosnell et al., 2019; Osuna et al., 2019; Rosenzweig et al., 2019; Schaffer et al., 2019; Swagemakers et al., 2019	Neotropics, Brazil, United States, France, Ghana, Southeast Asia, Haiti, Costa Rica, Mexico, Cuba, Kenya, Cameron, East Europe, United States, Australia, Sweden, Nepal, France, Laos, sub-saharan Africa, Canada,, Italy, Mexico, India, Brazil, United Kingdom, Germany and Austria	SE,ST,NN
	Physics/ Mathematics	1	Musshoff and Hirschauer, 2008	Germany and Austria	ST
Inhibitors (what factors inhibit change?)	Ecology/Natural Science	0			
	Social Science	30	Hill and MacRae, 1992; Meares, 1997; Guthman, 1998; Peter et al., 2000; Zaal and Oostendorp, 2002; Bouahom et al., 2004; Carolan, 2005; González and Nigh, 2005; Hall and Mogyorody, 2007; Pearson, 2007; Musshoff and Hirschauer, 2008; Cranfield et al., 2010; Lamine, 2011; Marini et al., 2011; Sutherland et al., 2012; Blesh and Wolf, 2014; Chantre and Cardona, 2014; Patil et al., 2014; Thornton and Herrero, 2015; Calo and De Master, 2016; Riley, 2016; Salvini et al., 2016; Šumane et al., 2018; Chieco et al., 2019; Gosnell et al., 2019; Osuna et al., 2019; Rosenzweig et al., 2019; Schaffer et al., 2019; Swagemakers et al., 2019; Tankha et al., 2020	Europe, United States, Australia, Sweden, Laos, sub-saharan Africa, Kenya, France, Canada,, Italy, Mexico, India, Brazil, United Kingdom, Germany and Austria	SE,ST,NN

(Continued)

TABLE 2 | Continued

Theoretical concept	Disciplines	#	Papers	Study locations	CF
	Physics/ Mathematics	1	Musshoff and Hirschauer, 2008	Germany and Austria	ST
Modes of change (how are changes experienced?)	Ecology/Natural Science	0			
	Social Science	2	Musshoff and Hirschauer, 2008; Lamine, 2011; Liu and Liu, 2016; Riley, 2016	China, United States, United Kingdom, Germany and Austria	SE,ST,NN
	Physics/ Mathematics	1	Musshoff and Hirschauer, 2008	Germany and Austria	ST

We classify papers into the five key theoretical concepts, three disciplines. We summarize the number of papers in each category (#) and identify the study locations (including countries and regions) and conceptual framework (CF) applicable to the studies. The frameworks are socio-ecological framework (SE), socio-technological framework (ST), and norms-and-networks framework (NN).

contributions from mathematics and physics to the agricultural transition literature is even larger when focusing on alternative agricultures apart from agroecology (**Table 2**). The majority of contributions from these two disciplines were associated with agroecological transitions, which may indicate disciplinary allegiance to this term or field (**Tables 1**, **2**). In fact, all but 1 of the 37 additional papers we added in this expansion were strictly social science papers, suggesting that agroecological transitions has greater disciplinary diversity.

We found that many of the agents, drivers and barriers discussed in the agroecological transition literature are also discussed in the literature on transitions into these other alternative agricultural systems. For example, climate change is also a primary driver for prompting shifts to climate-smart agriculture. This incentivizes technological advancement by promising greater resilience of crop systems in a changing climate (Descheemaeker et al., 2016; Long et al., 2016; Salvini et al., 2016; Chieco et al., 2019; Osuna et al., 2019; Tankha et al., 2020). As in agroecological transitions, lack of market access and land tenure can prevent transitions, as exemplified in the case of small-holder farmers transitioning into climate-smart agriculture in sub-Saharan Africa (Descheemaeker et al., 2016). In the Karnataka state of India, financial risk poses similar challenges for transitions into organic farming (Patil et al., 2014).

Our expanded search did focus more strongly on a number of concepts that are still useful in the context of agroecological transitions. Firstly, one key agent identified more strongly in this literature was the female farmer. Many studies suggested that female farmers are more likely involved in vegetable farms and mixed livestock and cash crop farms rather than field crop farms, where mechanization and capital-reliant production is higher (Hall and Mogyorody, 2007). This was ascribed to women having less access to financial capital and the limitation of traditional female farming roles that keep women from working heavy-duty machinery like tractors and handling finances (Meares, 1997; Peter et al., 2000; Saugeres, 2002). Secondly, health and safety concerns were in some cases a more predominant driver than economics for transitions into alternative agricultures (Cranfield et al., 2010). Advocating for the health and safety benefits of avoiding pesticides and other harmful agrochemicals affecting farmers, neighboring communities and consumers are useful in encouraging adoption of agroecology as well. Thirdly, policies that encourage voluntary participation, rather than coercive policing, may help motivate transitions. This lesson from game theory allows embedded actors to design policy bargains and leverage their technologies to facilitate the achievement of Pareto optima (Tankha et al., 2020). Thus, policies issued by the government or non-governmental organizations that reward the adoption of agroecological practices and sharing of knowledge could be strategically designed to motivate transitions. Fourthly, our expanded search identified a need to stimulate social learning and collective action to facilitate the socio-institutional change that is necessary for success (Salvini et al., 2016). Social learning and collective action are clearly important to the social movement component of agroecology, which demands extensive re-wiring of the global food system. Building a new social norm and community understanding could greatly facilitate transitions. Lastly, these additional studies stressed the necessity for co-creation through farmer-scientists alliances and improved consumer-farmer communications that work to imagine and build new food systems including the construction of new infrastructure than can support transitions (González and Nigh, 2005; Šumane et al., 2018). Though each alternative agriculture has accrued its own divisional camps amongst practitioners, consumers and academics alike, we suggest that their similar goals and challenges should be channeled to more effectively move toward a sustainable future.

SHIFTING CHAYANOVIAN BALANCES: A MECHANISM FOR CHANGE

Struck by the parallels of today's agricultural system and Chayanov's original thesis, van der Ploeg recently revived and extended the concept of Chayanovian balances to provide a general mechanism behind food systems change (van der Ploeg, 2009). According to van der Ploeg, modern peasants are driven by the desire to balance multiple needs. These include the utility and drudgery of work that was originally proposed by Chayanov, but also many additional balances (van der Ploeg, 2009). These include a balance between autonomy and dependency, which describes a pull between the independent management of a farm and reliance on support from external factors such as institutions and markets. Farmers also balance the reproduction and production of the farm, which describes a tradeoff between the capacity for a farm to produce in the future and the present. That is to say, intensive use of the socio-ecological resources of a farm now may hinder the ability of the farm to produce sustainably into the future. Finally, van der Ploeg argues that farmers also seek a balance between the internal and external use of farm resources. For example, farmers can use food produced on farms to provide food security for the family or exchange it for money or other goods (van der Ploeg, 2009; Mestre et al., 2019).

Authors have since used these balances to provide a mechanism to explain the range of agricultural forms, or "farms in between" observed under varying socio-ecological conditions. For example, Puerto Rican coffee farms range from small-family run operations to large-scale conventional systems, which varied greatly in their capacity to rebuild following recent hurricane events (McCune et al., 2019). Larger farms were the only farms with the financial capital necessary to rebuild, which the authors argue exemplifies a loss of autonomy in the autonomy-dependency balance of Puerto Rican farms. Combined with a dwindling labor force and lack of external resources to hire additional wage laborers, small family farms were forced to depend on government subsidies if they were to continue farming (McCune et al., 2019). Vandermeer and Perfecto have long argued that there is a non-linear balance between the necessary population required to work a farm and the size of the population that it can sustainably support, which depends also on the technologies employed in farm production (Vandermeer and Perfecto, 2012). They argue that as environmental conditions shift to favor technology, farms will move from small low-tech (peasant) to large high-tech (capitalist) syndromes, not unlike the shifts McCune observed in Puerto Rican coffee farms after hurricanes Irma and Maria. In Panama, the extent to which trees are incorporated in grazing pasturelands arguably represents a range of balances between the future reproductive capacity that trees provide (i.e., water, soil conservation and shade for animals) and the immediate production capacity of the farm (i.e., grass available for cattle production) (Mestre et al., 2019). All of these authors argue that shifting balances can drive transitions between alternative syndromes of production.

CHAYANOVIAN BALANCES TRANSLATED

Here we attempt to translate the concept of Chayanovian balances into a mathematical framework that can be used to understand the putative stability of peasant and capitalist farming syndromes. We suggest that Chayanovian balances can be interpreted as the difference between the overall cost (negative curve) and benefit (positive curve) of a particular farming style that can range from peasant to capitalist farming extremes (**Figure 2**). We examine a case when changes in a driver variable cause the benefits and costs of an increasingly capitalist farming style to increase. However, the relative balance between these costs and benefits will depend on a variety of complex socio-ecological factors, which we reviewed in detail earlier (**Figure 1**, **Table 1**). Assuming that farming itself has some initial benefits above its costs, we would expect peasant agriculture to develop as some driver variable, for example, the homogenization of diets, increases (**Figure 2A**). If the peasant syndrome is stable, the costs of pursuing a slightly more capitalist farming style should exceed its benefits, pulling farmers back into the peasant state despite increases in the driver variable. This makes sense if the rise in benefits of a capitalist farming style accrue in a non-linear convex fashion (**Figure 2A**). For example, the benefits of investing in a monoculture to accommodate small changes in consumer diets may only present if a farmer has the necessary social connections or reputation to sell produce at wholesale markets and may not exceed the costs to the environment that a farmer is balancing. If the peasant state is unstable, the costs of farming would exist below the benefits, which can drive the dynamics toward the origin, representing the loss of the peasant syndrome. Land dispossession, transitions to wage labor and rural out-migration can be represented by such a scenario (**Figure 2B**).

However, at some point, the benefits of becoming increasingly capitalist may outweigh the costs, moving farmers toward the capitalist alternative (**Figure 2A**). This process could theoretically continue indefinitely, implying that the capitalist syndrome is unstable. In this scenario, capitalist farming would exhibit uncontrolled growth, as capitalism itself is expected to behave (Olivier, 2005). From a mathematical perspective, the capitalist farming syndrome is only stable if the benefits of capitalism eventually saturate, causing the benefits curve to become non-linear concave (**Figure 2B**). Since farming systems are beholden to biological and physical constraints including for example, total land and photosynthetic capacity, we feel that this is a more realistic model. Theoretically, advances in technology could prevent the realization of these maxima. However, by assuming that maximums to capitalist farming benefits do exist, peasant and capitalist farming syndromes are easily represented as alternative stable states in a dynamic systems framework (**Figure 2C**).

BALANCES AS INFLECTION POINTS AND COSTS AS SLOPES

From this framework we can also visualize how shifts in Chayanovian balances, or the degree of negative consequences, can similarly trigger transitions. According to van der Ploeg, farming styles are based on balances between many conflicting needs. Farming styles are adopted according to how these balances are met given external socio-ecological conditions, which we represent as drivers of change moving a system between alternative farming syndromes (**Figure 2C**). However, the values, resource capacities and opinions of farmers are highly individualized and likely to affect the ways in which Chayanovian balances are conceived. Depending on the agent of change (as discussed previously), this can have dramatic

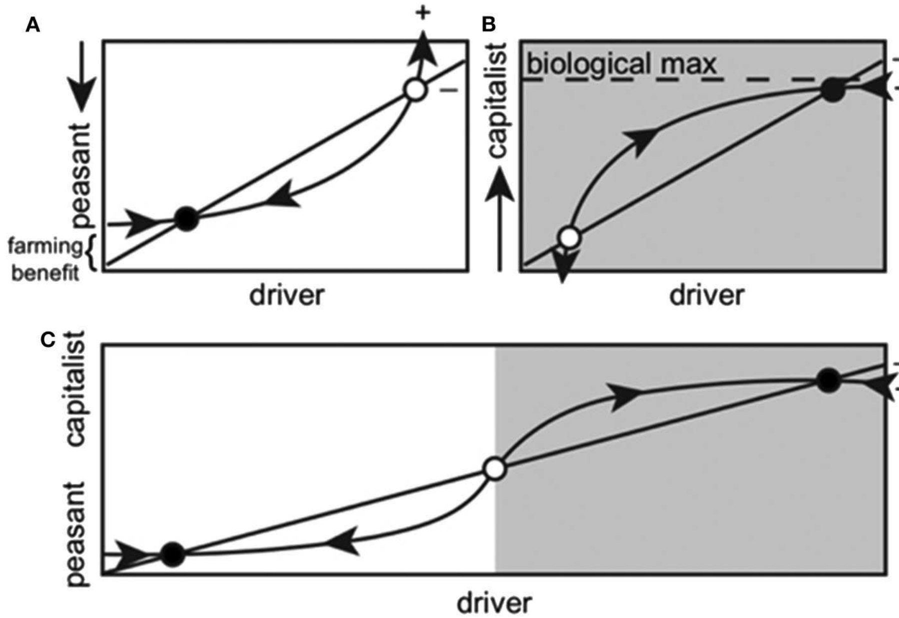

FIGURE 2 | Theorizing stability of farming syndromes. Phase diagram of Chayanovian balances interpreted as the relative costs (–) and benefits (+) of farming styles (y axis) ranging from peasant to capitalist extremes in response to a driver of change (x axis). Points where costs and benefits are equal represent equilibria with stable points represented by closed dots and unstable represented by open. Arrows indicate direction of flow in the system. **(A)** A stable peasant syndrome represented by an equilibrium low on the y axis where the benefits to farming (+) outweigh the costs (–) at the origin where the driver of system change is low and that the costs of moving away from the peasant equilibrium are higher than the benefits when the driver increases. **(B)** A stable capitalist syndrome represented by an equilibrium high on the x axis where benefits of capitalist farming rise above costs until they reach a biological maximum (dashed line). **(C)** When both the peasant and capitalist syndromes are stable, they are separated by an unstable equilibrium, which represents the inflection point where Chayanovian balances favor neither syndrome. Unshaded and shaded areas represent parameter regions for driver variable where peasant or capitalist syndromes, respectively, are attractive.

consequences for system dynamics. For example, the tolerance for changes in a driver variable might be such that the point of inflection for a given farmer's benefit curve may be much lower (blue dotted curve) than another's (green dashed curve) (**Figure 3A**). Similarly, different farms may experience different degrees of costs. For example, farms in colder climates may experience less damage from climate change (blue dotted line) than farms in the tropics (green dashed line) (**Figure 3B**). If the inflection point for these balances or the rate in which negative consequences of a capitalist farming system were to increase (i.e., from sustainability incentives or escalating effects of climate change), a farm or farmer in a capitalist syndrome could move suddenly into the alternative peasant syndrome (**Figure 3C**). From there, reducing the cost slope or inflection point (ie. due to fossil fuel subsidies or increased crop productivity from carbon fertilization effects) could cause a critical transition in the reverse direction from peasant to capitalist syndromes (**Figure 3C**).

INHIBITORS OF REGRESSION: SUSTAINING THE PEASANT SYNDROME

In order for agroecological transitions to have long-term impacts, transitions to peasant syndromes of production would need to be sustained. From a mathematical perspective, this requires the peasant syndrome to be stable so that the benefits of becoming increasingly capitalist should outweigh its costs and that there must be some non-zero benefit of farming that would prevent its total abandonment (**Figure 2A**). From our review of the literature, the latter may depend critically on government policy and public investment to foster an environment that makes peasant farming a secure and remunerative career (Schipanski et al., 2016; McCune et al., 2019). The former requires placing the peasant syndrome at an advantage over the capitalist alternative. This is a difficult feat, but our literature review suggests that sustained accumulation and transference of local agroecological knowledge may help peasant agriculture more effectively adapt to changing climatic and social conditions thereby creating a potential competitive advantage. Securing a polycentric distributional system that supports local agroecological farms and allows them to compete against large food corporations that have so far lobbied successfully to secure advantages in global food policy may also help raise the benefits and reduce the costs of the peasant syndrome.

LESSONS FROM A THEORETICAL PERSPECTIVE

Modes of Change

Pace

We believe that a mathematical perspective on agroecological transitions provides critical insight on the pace of change to

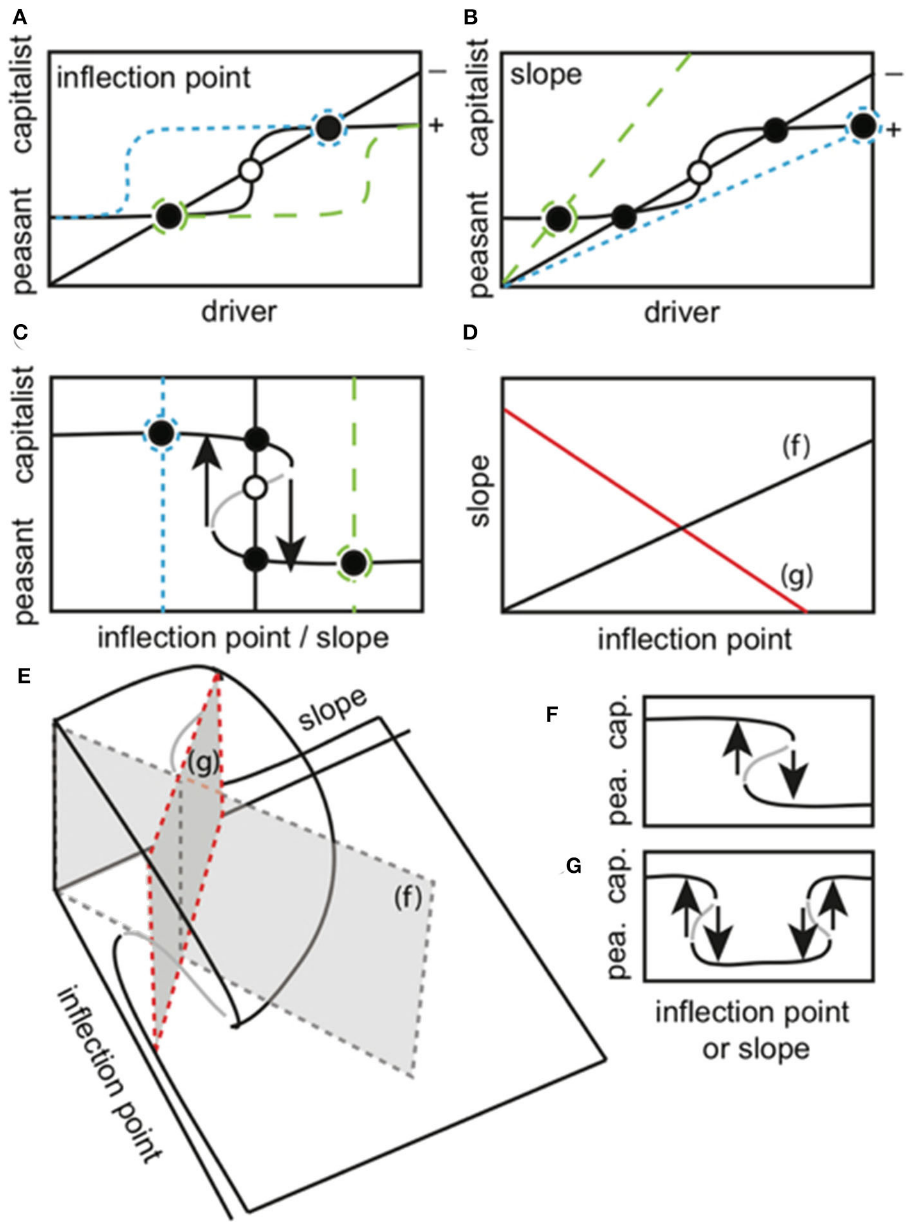

FIGURE 3 | Path dependence of farming syndromes. **(A)** Same phase diagram as **(C)** of **Figure 2** when inflection point of Chayanovian balances decreases (blue dotted line) or increases (green dashed line) so that only the capitalist or peasant equilibrium (solid points) is present. Black curves represent relative costs (–) and benefits (+) of farming styles. Points where costs and benefits are equal represent equilibria with stable points represented by closed dots and unstable represented by open. **(B)** Phase diagram showing elimination of all but one equilibrium when decreasing (blue dotted line) or increasing (green dashed line) the slope of the cost curve. **(C)** Expected results of incremental shifts to the inflection point of the benefit curve or slope of the cost curve in **(A,B)** on the type of agriculture conducted. Vertical lines in C correspond to the low (blue dashed) and high (green dashed) parameters visualized in **(A,B)**. System moves from having a single capitalist equilibrium to two alternative stable equilibrium with an unstable equilibrium at the middle of the peasant and capitalist syndromes to a single peasant equilibrium as these second order drivers (x axis) increase. Arrows indicate direction of flow in the system. **(D)** Two possible correlations between driver variables, positive (black line) and negative (red line). **(E)** 3-D phase diagram when both second order drivers (slope, inflection point) change simultaneously. Cross sections represent transition pathways assuming correlations in **(D)**. **(F)** Expected phase diagram for positive correlation between drivers. **(G)** Expected phase diagram for negative correlation between drivers.

be expected. Recent work by Titonell laid out an incremental vision of change in the food system (Tittonell, 2014). He argues that full progression into an agroecological alternative starts with small changes to current systems including increased eco-efficiency (i.e., less food waste in processing), followed by input substitution (i.e., nitrogen fixers for fertilizer), systems re-design (i.e., markets for organic produce), finally arriving in agroecological landscapes and food systems that fully incorporate social and ecological integrity into system design (i.e., just and sustainable food systems). At the same time, Titonell suggests that technical and institutional innovations can drive a critical transition, which implies that the rate of agroecological transformation should suddenly increase after a period of little to no change (Scheffer and Carpenter, 2003). The green revolution can itself be interpreted as a sudden and dramatic shift from the peasant to capitalist syndrome (**Figure 3C**). Though on the surface, change in the food system toward agroecology may at first appear slow and inconsequential, small changes in drivers that influence Chayanovian balances or the degree of negative consequences could theoretically induce a large-scale transition toward agroecology with little warning. Such a perspective provides hope that a slow rise in "green-washed" sustainable food movements may actually help by accumulating the social capital necessary to form social norms and quickly escalate sustainable food movements into change that fully incorporates the social aspects of agroecology.

Path Dependence

Critical transitions are often associated with hysteresis, which means that a system is path dependent. Since there is a range of parameter values for which a system can exist in either of the alternative stable states, the state of the system within this critical zone depends entirely on initial conditions (**Figure 3C**). Theory predicts that if we begin in a capitalist syndrome and shift Chayanovian balances to favor the peasant alternative, we will remain in the capitalist state until it is no longer viable. Though there is a range of conditions in which both peasant and capitalist syndromes are viable, if we begin in the capitalist syndrome we will stay there since it is stable, making the alternative peasant syndrome impossible to reach until the capitalist syndrome destabilizes (**Figure 3C**). If we were instead to begin in the peasant syndrome and move backward, theory dictates that we will remain in the peasant syndrome until it destabilizes, and we are forced into the capitalist syndrome. This mathematical perspective may help explain loyalties to farming styles despite the existence of potentially superior alternatives. For example, inducing capitalist farms to transition to agroecological alternatives is notably difficult and slow. The barriers to transition that were previously reviewed may indicate the presence of negative feedback in the system, which keeps farmers locked-in to the state of the farm they inherit despite the demonstrated viability of an alternative system that exists under the same conditions.

There are many examples from the social literature of farmers becoming locked into syndromes of production, whether that syndrome is peasant or capitalist agriculture. So-called "poverty traps" and "gilded traps" provide many relevant examples (Hanjra et al., 2009; Valkila, 2009; Tittonell and Giller, 2013; Boonstra and de Boer, 2014; Cox et al., 2019). Fair-trade organic coffee in Nicaragua has been called a poverty trap. The certification process and restrictions to markets that come with certification may keep farmers tied to small-scale low productivity modes of production that prevent wealth accumulation (Valkila, 2009). On the other hand, Dominican rice farms provide an example of gilded traps, where adoption of new technologies including chemical inputs and mechanization lock farmers into capitalist syndromes of production. Here, the accumulation of significant debts, dependence on technical assistance and lack of alternative farm models to emulate, keep farmers locked into capitalist production modes (Cox et al., 2019). In both cases, feedback between management regimes and social outcomes creates a stability to the syndrome of production that hinders transition to the alternative.

Complexity

The question of what has or can drive transitions to agroecology is complicated by the incredible diversity of drivers, agents and scales to consider (**Figure 1**). We hope that this theoretical framework is useful for organizing that complexity and revealing some of its implications for future food movements.

For example, in this paper we demonstrate that drivers of food system change can operate at two theoretical levels. Drivers at the first level affect the relative balance between the costs and benefits of a food syndrome, creating a threshold for which one syndrome or another becomes attractive (**Figure 2C**). If a driver is below this threshold, the costs of pursuing a more capitalist farming style are below the benefits and we would expect the system to move toward the peasant syndrome. If the driver rises above this threshold, then the system should move toward the capitalist threshold where the benefits outweigh the costs (**Figure 2C**). However, shifting perceptions of those benefits and costs can serve as a second-order driver of change (**Figure 3**). Changes to these perceptions cause transitions between syndromes to be critical with a zone of hysteresis where syndromes become alternative stable states (**Figure 3C**). In this zone, both states are attractive, thus the state of the system is determined by initial conditions. This means that in this zone, peasants will remain peasants even when the system is changing to favor capitalist farms, and capitalists will remain capitalist even when the system is changing to favor peasant farms.

Though there are numerous studies that identify different drivers of food systems change, here we suggest that interpreting whether these drivers are expected to operate at the first or second order could have potentially important consequences for policy. First order drivers should directly influence Chayanovian balances, while second order drivers influence perceptions of those balances. Based on our review of the literature, first order drivers may include land access and tenure and financial capital because they critically determine the costs and benefits of farming (**Table 3**). For a first order driver, policy could theoretically reverse conditions to recover a previously dominant agricultural syndrome in a predictable manner (**Figure 2C**). However, if a driver affects agricultural systems at the second order, small changes to the driver could have long-term consequences (**Figure 3C**). These drivers may include the social capital obtained horizontally via farmer to farmer connections, social justice and equity and environmental degradation because these factors influence how costs and benefits of farming are perceived and are subject to agent tolerances or context dependence

TABLE 3 | Drivers of agroecological transitions and their justifications for operating as a first order driver (1) by delineating the thresholds where cost/benefit ratios favor capitalist or peasant farming syndromes or a second order driver (2) by influencing the perceptions of costs and benefits where agent tolerance and specific context is particularly important.

Driver	Order(s)	Justification
Land access and tenure	1	Critically determines whether farmers have access to land and for how long
Financial capital (income, subsidies, insurance)	1	Critically determines financial risk
Horizontal social capital (farmer to farmer support)	2	Changes perceptions of risk and reward
Vertical social capital (institutional support)	1/2	May provide actual financial support, but also changes perceptions of risk and reward
Social justice and equity	2	Changes perceptions of risk and reward
Decentralization of markets	1/2	Increases access to local markets, but also changes perceptions of risk and reward
Environmental degradation	2	Changes perceptions of risk and reward

(**Table 1**). These subjective perceptions add a non-linearity that keeps farms from moving to viable alternatives. For this reason, we expect that second order drivers are more likely than primary drivers to cause poverty and gilded traps where farmers become trapped in non-ideal agricultural syndromes (Hanjra et al., 2009; Valkila, 2009; Tittonell and Giller, 2013; Boonstra and de Boer, 2014; Cox et al., 2019). Some drivers including the vertical social capital obtained through institutional support and decentralized markets were hard to classify as only operating at primary or secondary levels. These drivers may directly affect tangible costs and benefits such as financial subsidies and access to markets, but also change agent perceptions of risks and rewards by creating new social norms (**Table 3**). We suggest that future work deconstructing how drivers influence the pace and reversibility of food system change is necessary.

Multiple Pathways

The proposition of multiple simultaneous drivers of food system change implies that there are also multiple potential pathways to an agroecological alternative. Many drivers discussed in the literature are interrelated and can operate at the same time, but not necessarily in the same direction (**Figure 3D**, **Tables 1–3**).

In Chile, both inequality and environmental degradation are increasing rapidly. Dry and hot environmental conditions continue to worsen amidst a politically unstable climate where water rights do not extend to poverty-stricken peasant farmers (Larrain, 2012; Valdés-Pineda et al., 2014). However, in some of the colder regions in the world, environmental conditions may be improving, while inequity increases. For example, climate change has extended the growing season of the northern United States. This has caused increased migration of farmworkers to the region and a greater incidence of ICE raids under the current administration (Linderholm, 2006; Hing, 2009; Jenkins et al., 2009). Since so many potential drivers of agricultural change operate simultaneously but differentially, we expect many unique pathways to agroecology to exist.

Recent advances in critical transition theory suggests that correlations between multiple driver variables can have dramatic consequences for managed systems (Ong and Vandermeer, 2018). We examine cases where positive shifts in both the inflection point of Chayanovian balances and the cost slope occur and cases where these drivers are negatively correlated (**Figure 3**). To motivate this, we provide a few relevant case studies. In the Global South, La Via Campesina has gained considerable ground in promoting the way of the peasant, but at the same time, climate change continues to exacerbate drought and increase the frequency of extreme weather events (Baethgen, 1997; Torrez, 2011; Rosset and Martinez-Torres, 2013). Here our two drivers are positively correlated. However, developing countries such as China are experiencing industrial booms that shift food systems in favor of conventional modes despite increasingly severe impacts on the environment and human health, suggesting that drivers can also be negatively correlated (Li et al., 2015). Though changes to each individual driver can lead to critical transitions with hysteresis, i.e., path dependence, when both of these drivers change simultaneously, a 3-dimensional agricultural syndrome space is created where we can visualize the multiple pathways toward agroecology (**Figure 3**). When the two drivers are positively correlated, we expect a critical transition that looks the same as if only one driver was affected. However, if the two drivers are negatively correlated, a sudden transition toward the peasant syndrome could be followed by a second critical transition back toward the capitalist (**Figure 3**). This theoretical perspective implies that if we were to ignore the effects of correlated driver variables, shifts toward agroecology could be unwittingly undermined. For example, an extensive urban agriculture system developed in Cuba following the collapse of the Soviet Union and the imposition of strict trade blockades. This history has led many to fear that improving trade relations between Cuba and the U.S. could threaten hard-won advances in agroecology (Fernandez et al., 2018). Though many farmers in Cuba support both agroecology and improved trade relations, underlying shifts in environmental threats including costly tropical storms and hurricanes in the Caribbean could theoretically cause agriculture to shift toward capitalist systems like in Puerto Rico, where only large farms were able to rebuild post-hurricane Irma and Maria (McCune et al., 2019). Our theoretical perspective provides evidence that a holistic view is imperative for sustaining changes to agroecological alternatives. The existence of multiple drivers and socio-ecological contexts in agriculture implies that there are no silver bullets to systemic food system change and that

TABLE 4 | Summary of locations for reviewed case studies.

	Agroecological transition	Alternative agricultural transition	Both
U.S. and Canada	2	12	14
Latin America	14	3	17
Europe	4	11	15
Asia	1	5	6
Africa	2	3	5
Oceania	0	1	1
Total	23	35	58

Americas comprise majority of the cases (53.4%), followed by Europe (25.9%) for all cases of agroecological transitions and alternative agriculture transitions combined.

successful transitions toward agroecology can theoretically be undermined if the effects of multiple conflicting drivers are not considered in policy and management.

TRANSDISCIPLINARY PROBLEMS

There is value in having a theoretical perspective on the transdisciplinary problem of food system change. For one, our theoretical perspective allows us to bridge the social, ecological and mathematical disciplines so that we can fully integrate the available knowledge on how agroecological transitions have happened in the past and might happen in the future. From our review of the literature, we discovered that the majority of current knowledge on theoretical concepts related to agroecological transitions is actually derived from the social sciences rather than ecology, mathematics or physics (**Tables 1**, **2**). Though surprising, this finding implies that there is significant potential for these disciplines to contribute more theory to food systems change. Perspectives from the natural and physical sciences are particularly lacking in the socio-technological framework (**Tables 1**, **2**). These insights are crucial for understanding how social factors are modified by environmental constraints to change. Though we know that human management of natural systems are inducing potentially irreversible impacts on ecosystems, we know very little about how societies alter management practices in response to these physical constraints and whether that has significant impacts on the recovery of ecosystems. However, the significant theoretical contribution of social science is important to highlight. Though often pitted against natural and physical science, both the qualitative and quantitative insights of social science are clearly important in understanding the agents, barriers, drivers and mechanisms behind agroecological transitions. In the end, synthetic multidisciplinary work is necessary to fully understand food system change.

Ultimately, agroecological transitions are carried out by farmers, consumers, grassroots movements and institutions striving for change. Are production syndromes stable? Can farmers escape traps? Are drivers manipulatable? Which agents can drive the fastest or largest changes, and how can change be sustained? Our theoretical perspective has provided some predictions to these questions, but empirical data must be collected to fully test theory and effectively support food movements. The current data we have on agroecological transitions comes primarily from Latin America (**Tables 1**, **4**), and if we are to inform policies that are to induce speedy global food systems change to agroecology, more work needs to be done in other regions of the world. Out of 23 papers that discussed specific case studies (excluding reviews) of agroecological transition where we can pinpoint a specific geographic region, 16 (70%) were conducted in the Americas (North, Central and South), mostly in Latin America (**Table 4**). Expanding our search to include transitions to other alternative agricultures did not change the fact that the largest source of papers came from the Americas (15/35, 52%), though North America became much more dominant than Latin America. We found many more studies from Europe (11, 31%) than in the agroecological transition literature (4, 17%). Representation by Asia was also higher in the expanded search (5, 14%) compared to only 1 study in our agroecology review (0.04%). The distributional shift suggests that agroecology is less studied outside of Latin America, but regional representation for alternative agricultures are not much better (**Table 4**). Our review was also limited to peer reviewed articles written in English, which may have skewed our results to favor the Americas. The agroecological revolution does have strong roots in Latin America and our review suggests that its discourse remains primarily within this center of origin. Yet if agroecology is to spread to other nations, researchers in this area will need to develop transition literature that is relevant to other regions where other alternatives are currently more commonly addressed. The Americas, Europe and Asia currently produce the majority of global calories, which are concentrated in commodity crops (FAOSTAT, 2018). Agroecological shifts in these regions could help diversify food chains. Over-representation by the Americas may diminish the role of other agents, drivers and inhibitors of change in Europe, Asia and other regions where agroecological farming may already persist. For example, social norms and networks may look very different in different regions and cultures depending, for instance, on the levels of importance ascribed to the family unit, technology and the environment. Though transitions in each region will be context dependent, focusing on collecting information on shared theoretical concepts including the syndromes of production, agents, barriers and drivers of change will help create a more thorough and generalizable picture of agroecological transitions (**Tables 1**, **2**). In fact, the theoretical perspective on agroecological transitions presented here teaches us to embrace rather than avoid context dependency. Despite the disparate and significant obstacles to change, complexity also presents opportunities. Though there may be no silver bullet approaches to food systems change, paying particular attention to which drivers influence perceptions and value systems may help agents avoid social traps and discover new pathways to agroecology. If one path to agroecology fails, theory predicts that another path still exists. We suggest that taking a transdisciplinary approach may best help us get there.

AUTHOR CONTRIBUTIONS

TO and WL collaboratively reviewed the literature, drafted and edited the manuscript, figures, and tables.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2020.00091/full#supplementary-material

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