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Regenerative Agriculture in Transition: Practice, Outcomes, and the Expansion of a Contested Field

A dissertation submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in

Management of Complex Systems

by

Nícolas Moreno Gonçalves

Dissertation Committee:
Assistant Professor Tea Lempiälä (Principal Advisor), Chair
Professor John Abatzoglou (Co-Advisor)
Associate Professor Rebecca Ryals

2026

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For my beloved parents, Altamir and Rosangela,
through your love and perseverance,
we came far from our small Vera Cruz.



The municipal coat of arms shown here is from Vera Cruz, a small rural town in the interior of São Paulo, Brazil, founded in 1934 during the expansion of the state's coffee frontier, historically shaped by agricultural traditions and immigrant communities, and today home to roughly 10,000 residents.

The Dissertation of Nícolas Moreno Gonçalves is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

_____

Professor John Abatzoglou

_____

Associate Professor Rebecca Ryals

_____

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It feels unavoidable to me to start an acknowledgement section without acknowledging how strikingly challenging it is to write one. The challenge here does not stem from the writing process, of which in itself is challenging enough for me, but it is so mostly for the huge task of translating into words – and consequently trying to capture all the sentiment in those words – all the gratitude for those who helped me through my graduate path, culminating in this moment. Still, I hope that all the people mentioned here, and those who were left out through a fault of my own and should have been mentioned, can feel all the appreciation I have for them.

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VITA

Nícolas Moreno Gonçalves

---

1. Professional Summary

Interdisciplinary researcher specializing in agricultural systems, regenerative agriculture, and sustainability transitions, with experience across the United States and Brazil. Combines field-based research, stakeholder engagement, and mixed-methods analysis to examine how agricultural systems are implemented, coordinated, and evaluated under complex socio-ecological and institutional conditions. My work integrates environmental assessment, sustainability governance, and land-use systems analysis to investigate the dynamics shaping transitions toward more resilient food systems.

2. Education

Ph.D. Candidate, Management of Complex Systems, University of California, Merced

• Dissertation: *Sustainability transitions in regenerative agriculture, examining governance dynamics, intermediary organizations, and institutional narratives shaping pathways of agricultural system transformation.*

M.S., Biodiversity Conservation and Sustainable Development, Instituto de Pesquisa Ecológica (IPE), Brazil (2018)

• Thesis: *Economic valuation of carbon sequestration in coffee agroforestry systems.*

B.S., Biology, University of São Paulo, Brazil (2014)

• Project*: Phytosociological dynamics of a rainforest fragment under management of the invasive species Archontophoenix cunninghamiana.*

B.S., Biology, Exchange Program, Lisbon University, Portugal (2012–2013)

• Project: *Regulating actors of pond temperature across two Mediterranean seasons (winter and spring).*

3. Publications & Presentations

Peer-reviewed

• **Goncalves, N.,** Andrade, D., Batista, A. et al. Potential economic impact of carbon sequestration in coffee agroforestry systems. *Agroforest Systems* (2021). doi: https://doi.org/10.1007/s10457-020-00569-4

• Seipp, K.Q., Maurer, T., Elias, M., Saksa, P., Keske, C., Oleson, K., Egoh, B., Cleveland, R., Nyelele, C., **Goncalves, N.,** and Hemes, K. A multi-benefit framework for funding forest management in fire-driven ecosystems across the Western US. *Journal of Environmental Management* (2023). doi: https://doi.org/10.1016/j.jenvman.2023.118270

Conference Presentations

• Jun 23–27, 2025 – **Goncalves, N.,** Lempiala, T. Unpacking Regenerative Agriculture: Social Movements, Cultural Framing, and Sustainability Transitions. 16th International Sustainability Conference (IST 25), Lisbon.

• Mar 24–25, 2022 – **Goncalves, N.,** Bernal, C., Keske, C. Barriers in adopting Precision Agriculture Technology in California's Central Valley. This Way To Sustainability Conference, Virtual.

• Jun 2019 – **Goncalves, N.,** Uezu, A., Cullen, L.Jr., Batista, A., Caixeta, D. Carbon sequestration and its potential economic impact in coffee agroforestry systems in São Paulo, Brazil. Contributed Talk. 16th AFTA Biennial Conference, Oregon State University.

4. Funding and Awards

Grants

• Total Funding Secured (≈ US$100k)
• 2025 – Graduate Dean's Dissertation Fellowship (US$27,000)
• 2024 – Ellis Fellowship (US$25,000)
• 2024 – McKenzie Scott Graduate Award (US$500)
• 2024–2025 – UC Merced Miguel Velez Fellowship (US$10,000)
• 2014–2015 – CAPES Undergraduate Scholarship (R$4,800)
• 2012–2013 – CNPq Undergraduate Scholarship to study abroad (e$11,500)
• 2010 – CNPq Undergraduate Scholarship (R$2,070)

Awards

• 2022 – Diversity and Culture of Inclusion Award, IoT4Ag ERC

5. Academic Service & Engagement

• Reviewer: *Journal of Environmental Management*
• Reviewer: *PLOS: Complex Systems*
• Sept 2024 – Screening of Common Ground, Merced, CA: *Organizer and Panel Moderator.*
• Jun 2021 – Dec 2022 – Vice-President, Student Leadership Council*; Graduate Student Liaison, IoT4Ag ERC, UC Merced.*

ABSTRACT

Regenerative Agriculture in Transition: Practice, Outcomes, and the Expansion of a Contested Field

by

Nícolas Moreno Gonçalves

Doctor of Philosophy in Management of Complex Systems

University of California, Merced, 2026

Assistant Professor Tea Lempiälä, Chair

Regenerative agriculture (RA) has gained prominence as a pathway for building more resilient agri-food systems in response to mounting environmental pressures. While research increasingly documents its environmental benefits, particularly for soil health and ecosystem functioning, its implications for consumptive water use remain less clearly understood. At the same time, RA remains conceptually unsettled, with limited clarity on how it develops and is coordinated as an alternative agricultural system in the context of sustainability transitions. In this dissertation, I address this gap by examining how regenerative agriculture is enacted in practice, materializes in measurable outcomes, and evolves as an emerging field under institutional complexity. To do so, I adopt a mixed-methods approach across three analytical dimensions. First, drawing on qualitative interviews and field observations, I analyze how regenerative practices, embedded in ecological processes, are formed and stabilized under institutional constraints using routine dynamics as an analytical lens. Second, I compare consumptive water use between matched regenerative and conventional almond orchards and vineyards in California, using evapotranspiration as a material account of these systems. Third, I examine RA as an emerging sustainability field, focusing on how it expands, is coordinated, and is structured within broader transition dynamics. My findings show that regenerative agriculture is not reducible to standardized practices but emerges through context-dependent socio-ecological routines, continuously adapted under ecological and institutional conditions. Empirically, regenerative systems do not increase consumptive water use relative to conventional systems, challenging assumptions that ecological improvements necessarily entail higher water demand. At the field level, RA develops through expansion without stabilization, in which participation broadens under converging landscape pressures while meanings, standards, and governance arrangements remain fragmented. Under these conditions, coordination is sustained through adaptive and provisional mechanisms rather than institutional consolidation. Overall, I develop an integrated account of regenerative agriculture that links practice formation, material outcomes, and field development. As a result, I contribute to sustainability transitions research by developing a micro-level, practice-based account of regenerative agriculture, empirically clarifying contested water-savings claims associated with regenerative practices, and showing how alternative systems can expand and persist without prior stabilization.

INTRODUCTION

Modern agriculture, often referred to as conventional or industrial agriculture, is a relatively recent configuration. Its contemporary form took shape in the decades following World War II, when industrial infrastructures built for mass-producing machinery and chemicals were repurposed toward food production (Mathias & Davis, 1996). Tractors replaced military equipment, and chemical compounds designed for wartime purposes were reformulated as fertilizers, herbicides, and pesticides (Mathias & Davis, 1996). What emerged was not merely a technological shift, but a reorientation in how agriculture itself was conceived: less as an ecological process, and more as a system to be optimized through industrial logic.

This transformation was both historically contingent and materially necessary. It responded to a rapidly growing population, the expansion of urban centers, and the increasing demand for reliable, scalable food production (Fitzgerald, 2003). In this context, agriculture came to mirror the principles of industrial efficiency, favoring specialization, standardization, and the large-scale cultivation of a narrow range of commodity crops (Fitzgerald, 2003). Over time, this approach led growers to break down inherently ecological farming systems into separate components, such as soil fertility, pest control, and crop productivity, and to address each of them through the application of chemically manufactured inputs. The result has been the consolidation of a production system dominated by monoculture and sustained by continuous human intervention.

In the book "One Size Fits None", Stephanie Anderson compares this narrow-minded farming view to horse blinders, in which "*the farmer can no longer see things like soil health, the environment, consumer health, and water quality – these are the distractions conventional agriculture seeks to remove from farmer's vision*" (Anderson, 2019, p. 210). With the passage of time, mounting scientific knowledge has shown that conventional agriculture is an environmentally unsustainable system, due mainly for two reasons, better worded by the long-time environmental essayist Wendel Berry: "*the first is that the industrial vision is perhaps inherently an oversimplifying vision […] the second reason […] is its wastefulness, […] there have always been unusable 'by-products'. Because industrial cycles are never complete*" (Berry, 2018, p. 116).

Over the past decades, this tension has become increasingly visible through a growing body of scientific evidence. Contemporary food systems are estimated to account for approximately 34% of global greenhouse gas emissions, with agricultural activities contributing the majority of these impacts (Crippa et al., 2021). Historical land use associated with agriculture has led to substantial losses of soil organic carbon, estimated at approximately 133 Pg globally, much of it occurring within the last two centuries (Sanderman et al., 2017). At the same time, agriculture remains the dominant user of freshwater resources, accounting for roughly 70% of global withdrawals, while contributing to widespread degradation of aquatic ecosystems (Foley et al., 2011). These patterns do not suggest a system in immediate collapse, but rather one whose operational logic generates cumulative pressures that are increasingly difficult to reconcile.

Yet, these dynamics unfold alongside an equally pressing imperative. Global population is projected to reach 9.7 billion by 2050, with corresponding increases in food demand (United Nations et al., 2019). Estimates suggest that agricultural production may need to expand by up to 70% to meet these needs (Bruinsma, 2009), even as the environmental constraints associated with land use, emissions, and resource depletion intensify. Agriculture already occupies approximately

half of the world's habitable land (Ritchie & Roser, 2023), and further expansion carries significant ecological costs. The challenge, therefore, is not simply one of replacing an inadequate system, but of navigating a condition in which productivity, environmental stability, and resource constraints are increasingly entangled.

In this context, regenerative agriculture (RA) has increasingly been framed as a systemic response to the ecological limitations of industrial agriculture (Lal, 2020; Shahmohamadloo et al., 2022). Rather than sustaining existing production systems, RA is framed as an approach that seeks to regenerate soil health, enhance ecosystem functioning, and re-establish the ecological foundations of agricultural production (Lal, 2020; Shahmohamadloo et al., 2022; White, 2020). Empirical studies increasingly support these claims, showing that regenerative systems can improve soil structure, increase soil organic carbon, and enhance nutrient cycling and microbial activity, thereby strengthening key ecosystem functions (Fenster et al., 2021; Kremen & Miles, 2012; Luján Soto et al., 2021).

Regenerative agriculture has also been associated with benefits that extend beyond environmental performance. Empirical work suggests that regenerative systems can improve farm profitability, even when yields are lower, by reducing dependence on costly external inputs and diversifying revenue streams (LaCanne & Lundgren, 2018). At the same time, RA has been linked to higher wellbeing and satisfaction with health among farmers, suggesting that its benefits may also include social dimensions of sustainability (Brown et al., 2021). Moreover, regenerative practices can enhance the nutritional profile of food (Montgomery et al., 2022), increasingly being connected to human health through emerging "Food is Medicine" initiatives, which frame healthy food as a clinical intervention (Mozaffarian et al., 2019; The Rockefeller Foundation, 2026). Consequently, this perspective position locally and regeneratively sourced food as capable of improving health outcomes while also generating new, more stable markets for farmers (Mozaffarian et al., 2019; The Rockefeller Foundation, 2026).

However, despite this growing attention, regenerative agriculture remains marked by persistent ambiguity and contestation (Newton et al., 2020). The term lacks a stable consensus definition and it is associated with divergent interpretations across actors, spanning different practices, objectives, and evaluative criteria (Congreves, 2025; Newton et al., 2020; Schreefel et al., 2020). At the same time, its rapid uptake across policy, corporate, and public domains has led to concerns over dilution, strategic appropriation, and "greenwashing," as actors mobilize the label while advancing heterogeneous and sometimes competing agendas (Wilson et al., 2025). As a result, regenerative agriculture is simultaneously expanding as a widely invoked solution while its meaning, scope, and standards remain unsettled.

These tensions are not unique to regenerative agriculture, but reflect broader patterns observed in efforts to transform agricultural systems toward more sustainable forms. Sustainability transitions scholarship has developed as a central field for understanding how established systems such as conventional agriculture change under mounting environmental and societal pressures. In this literature, change is conceptualized as a multi-level process involving interactions between emerging approaches, established regimes, and wider landscape developments (Geels, 2002; Geels & Schot, 2007). Rather than unfolding through discrete replacement, transitions are understood as gradual and uneven processes in which new approaches to farming emerge, interact with existing institutional arrangements, and reshape agricultural systems over time (Köhler et al., 2019; Markard et al., 2012). From this sustainability transitions framework, regenerative agriculture can be analyzed as an alternative agricultural system that attempts to reconfigure how agriculture is articulated, reproduced, and extended.

While the sustainability transitions framework provides a lens for understanding how agricultural systems are reconfigured at a macro level, regenerative agriculture as a field is organized through the enactment of practices. In this sense, routine dynamics offers a complementary micro-level analytical perspective. This literature conceptualizes organizing as constituted through recurrent patterns of action performed by multiple actors over time (Feldman & Pentland, 2003; Pentland et al., 2012). Rather than treating practices as fixed or pre-defined units, this theoretical lens emphasizes how these patterns are continuously enacted, with field stability emerging as an empirical outcome of ongoing performance rather than a given property of the system. Adopting a routine dynamics perspective directs attention to the processes through which regenerative practices are performed, as a means of understanding how patterns of action contribute to the development and stabilization of the field over time.

Beyond the enactment of practices, regenerative agriculture is also shaped by the outcomes it is expected to generate and how these outcomes are framed within broader sustainability transitions. Transitions literature has increasingly emphasized the role of expectations, narratives, and framing processes in guiding how alternative approaches are understood, evaluated, and supported (Geels, 2014; Lempiälä et al., 2019). In this sense, regenerative agriculture is not only defined by the practices through which it is performed, but also by its sustainability claims. Empirical studies have linked regenerative practices to improvements in soil structure, water retention, and ecosystem functioning, suggesting potential gains in resource efficiency (Fenster et al., 2021; Kremen & Miles, 2012). At the same time, Lankford & Orr (2022) highlight the complexity of interpreting such outcomes, as biophysical processes and measurement approaches can complicate how water use and efficiency are assessed in agricultural systems. Providing an empirical basis for assessing these outcomes offers a way to evaluate claims about regenerative agriculture and how they are mobilized to shape directionality within sustainability transitions.

Sustainability transitions, routine dynamics, and the study of material outcomes each offer distinct but complementary perspectives for examining regenerative agriculture. At the system level, sustainability transitions research provides a lens for understanding how alternative approaches emerge and develop within established agricultural regimes. At the level of practice, routine dynamics directs attention to how regenerative practices are performed through patterns of action and how these patterns stabilize over time. At the material level, better assessing the outcomes associated with regenerative agriculture help in shaping how this production system is interpreted and supported during processes of change. Considered jointly, I draw on these analytical lenses in this dissertation to address the following research question:

- How does regenerative agriculture perform, materialize, and develop as an alternative agricultural system in the context of sustainability transitions?

I address this question across three chapters, each examining regenerative agriculture from a distinct but complementary perspective. In the first chapter, I draw on routine dynamics and qualitative fieldwork to examine how regenerative practices are performed in context, focusing on how farmers experiment with, adapt, and stabilize patterns of action in relation to ecological conditions. In the second chapter, I analyze how the outcomes associated with these practices materialize in measurable terms, using field-level evapotranspiration data to assess water use as a key dimension of agricultural performance. In the third chapter, I examine how regenerative agriculture develops in relation to broader sustainability transitions, focusing on how the field expands, is interpreted, and is taken up across different actors and institutional settings.

All in all, my dissertation contributes by developing an analytically grounded account of how regenerative agriculture is enacted, evaluated, and sustained under conditions of ecological constraint and institutional incompleteness. Rather than treating regenerative agriculture as a coherent model or a set of predefined practices, it advances a perspective in which agricultural transformation is understood through the interplay between situated practice, material outcomes, and field-level dynamics.

First, I contribute with a practice-based account of how regenerative agriculture is formed and stabilized under ecological conditions. It shows that regenerative agriculture is not reducible to a set of transferable techniques but emerges through ongoing processes of routine enactment along with more-than-human actors. In doing so, it repositions agricultural change as a problem of practice formation and stabilization, rather than adoption of predefined innovations.

Second, I contribute with a material account of regenerative agriculture's environmental outcomes by providing an empirical basis to assess consumptive water use. By grounding regenerative claims in observed patterns of evapotranspiration, it clarifies that improvements in soil and ecological functioning do not mechanically translate into increased water demand. This contribution reframes how regenerative agriculture is evaluated, shifting from assumed co-benefits toward empirically specified environmental performance.

Third, I contribute to sustainability transitions research by identifying a distinct pattern of field development in which expansion occurs without prior stabilization. It shows that regenerative agriculture advances through heterogeneous participation and persistent ambiguity in meanings, standards, and governance, rather than through progressive alignment. Under these conditions, coordination is sustained through adaptive and provisional mechanisms, providing an alternative account of how emerging sustainability fields develop.

These contributions advance a multi-dimensional understanding of regenerative agriculture that links the formation of practices, the specification of material outcomes, and the dynamics of field development. In doing so, the dissertation offers a more precise basis for analyzing how alternative agricultural systems emerge and persist under ecological, empirical, and institutional constraints.

Methodological Considerations

This dissertation adopts a mixed-methods research design to examine regenerative agriculture as a complex and evolving phenomenon situated at the intersection of agricultural practice, environmental performance, and sustainability transitions. The research combines qualitative and quantitative approaches across three complementary analytical dimensions: the enactment of regenerative agriculture in practice, the material outcomes associated with these practices, and the broader dynamics through which regenerative agriculture develops as an emerging field. This design reflects the premise that regenerative agriculture cannot be adequately understood through a single methodological lens. While quantitative approaches provide a means of assessing material outcomes, such as consumptive water use, understanding how regenerative agriculture is performed, interpreted, and coordinated requires engagement with the meanings, experiences, and processes through which actors construct and navigate this contested domain. Consequently, the dissertation is ontologically grounded in a constructivist perspective that views social realities not as fixed entities to be discovered, but as continually produced and negotiated through situated interactions among actors, institutions, and ecological conditions.

Epistemologically, the dissertation is guided by an abductive logic of inquiry. Rather than proceeding through the deduction of hypotheses from pre-existing theory or through the purely inductive generation of theory from empirical observations, abductive analysis involves an iterative movement between empirical material and theoretical explanation. As Timmermans and Tavory (2012) argue, abductive inquiry is particularly suited to theory construction because it seeks to explain empirical surprises, anomalies, and puzzles through ongoing dialogue with existing theoretical traditions. In this dissertation, empirical observations were not treated as independent of theory, nor was theory imposed deductively upon the data. Instead, concepts from sustainability transitions research, routine dynamics, and field theory informed the initial analytical orientation while remaining open to revision through sustained engagement with empirical material. Throughout the research process, observations that challenged prevailing assumptions about regenerative agriculture, whether regarding the stabilization of ecological practices, the relationship between regenerative systems and water consumption, or the expansion of the field itself, served as opportunities for conceptual refinement and theoretical development.

The qualitative components of the dissertation draw on grounded theory principles as a systematic strategy for data analysis and concept development. Grounded theory has historically been associated with the inductive ambitions of Glaser and Strauss (2017), who developed the methodology as an alternative to deductive approaches that forced empirical observations into pre-existing theoretical frameworks. Their emphasis on constant comparison, theoretical sensitivity, and theory generation remains highly influential. However, the classical formulation of grounded theory has also been criticized for its objectivist assumptions and its portrayal of theory as emerging directly from data independent of prior theoretical commitments (Timmermans & Tavory, 2012; Timonen et al., 2018). Contemporary grounded theory scholarship has increasingly challenged this position, emphasizing the interpretive and reflexive character of qualitative inquiry (Charmaz, 2014). Following this development, I adopt a constructivist grounded theory orientation that understands categories and concepts as interpretive constructions generated through engagement between researcher, participants, and empirical material rather than as objective features waiting to be discovered. In this view, the value of grounded theory lies not in producing theory from a theoretical vacuum, but in providing a rigorous and systematic set of analytical practices through which empirical observations can be transformed into theoretically meaningful insights.

This position is also consistent with recent efforts to reconcile grounded theory with abductive reasoning. Rather than treating grounded theory as a purely inductive methodology, scholars have increasingly argued that its enduring contribution lies in the analytical practices it offers for theory construction, including iterative coding, memo writing, constant comparison, and the systematic examination of empirical variation (Timonen et al., 2018). These procedures create opportunities for identifying unexpected patterns and developing novel conceptual explanations while maintaining close engagement with empirical material. Accordingly, grounded theory informed the analytical procedures employed throughout the qualitative chapters of this dissertation, while abductive reasoning guided the broader process of theory development. Together, these approaches enabled the development of concepts and explanations that remained empirically grounded while simultaneously engaging with and extending existing theoretical conversations.

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CHAPTER 1: Ecological Routines in Regenerative Agriculture: A More-than-Human Perspective on Routine Dynamics

Abstract

Regenerative agriculture (RA) has gained prominence as a pathway toward more sustainable agri-food systems, yet it exhibits uneven development and limited stabilization as an alternative to conventional agriculture. Existing sustainability transitions research explains such patterns primarily through niche-regime dynamics but offers limited insight into how practices are reproduced and stabilized in such contexts. Through a routine dynamics perspective and drawing on 48 semi-structured interviews and field observations, I conceptualize RA as ecological routines and examine how practices are formed, sustained, and constrained under socio-ecological conditions. I develop the concept of ecological routines to capture recurrent patterns of action reproduced through sustained engagement with more-than-human processes, including soils, plants, and climatic dynamics. I show that these routines emerge within a regenerative system logic characterized by closed-loop ecological dependencies and structural context-dependence, where outcomes are mediated by delayed, non-linear, and place-specific feedback. I identify three core routine dynamics through which routines are formed and incrementally stabilized: ecological probing under uncertainty, constrained commitment and adaptive pacing, and decentralized ecological learning. Together, these dynamics explain how routines persist without converging into fixed or transferable practices. At the same time, I show that the broader reproduction of ecological routines is constrained by a conventional system logic embedded in epistemic, policy, financial, and infrastructural arrangements. These arrangements privilege standardization, predictability, and scalability, thereby disadvantaging routines dependent on ecological responsiveness and temporal adaptation. This study makes two contributions. First, it extends routine dynamics by specifying how routine reproduction unfolds under socio-ecological conditions, where material environments are generative and responsive rather than inert. Second, it provides a micro-process explanation for why sustainability transitions often remain partial and uneven in practice, showing how regime-level dynamics operate through the selective reproduction of routines.

1.1 Introduction

Research on socio-technical transitions has provided powerful frameworks for understanding regime stability, niche emergence, and long-term systemic change, emphasizing the co-evolution of technologies, institutions, markets, infrastructures, and cultural meanings (Geels, 2002; J. Köhler et al., 2019; Lempiälä et al., 2019; Markard et al., 2012). Despite growing scholarly and policy engagement with sustainability transitions in agri-food systems, progress toward environmentally resilient food systems remains slow, uneven, and frequently partial, pointing to limits in existing explanations and approaches (El Bilali, 2019; Hebinck et al., 2021; Volkov & Morkūnas, 2025). Across sectors, emerging sustainability fields often fail to consolidate into durable alternatives to dominant production systems, instead remaining fragmented, being absorbed into incumbent regimes, or stabilizing only in limited and context-specific forms (El Bilali, 2019; Fuenfschilling & Truffer, 2014; Schiller et al., 2020; Van Uden et al., 2024).

Agriculture provides an interesting manifestation of these patterns. Over the past decade, regenerative agriculture has gained growing traction across scientific, policy, corporate, and practitioner arenas (Congreves, 2025; Newton et al., 2020). Regenerative approaches are widely associated with improvements in soil health, biodiversity, water regulation, and system resilience under climate stress, and empirical research increasingly documents such outcomes under specific conditions (Baldwin-Kordick et al., 2022; Gosnell, 2022; Lal, 2020). At the same time, regenerative agriculture remains conceptually contested and institutionally fragile (Newton et al., 2020; Wilson et al., 2025). Definitions vary widely, certification schemes remain unstable, and the label is frequently appropriated without substantial changes to underlying production logics (Congreves, 2025; Cusworth et al., 2022; Tittonell et al., 2022). As a result, regenerative agriculture often persists as an adaptive, locally viable mode of farming rather than stabilizing as a broadly supported alternative to conventional agriculture (El Bilali, 2019; Schiller et al., 2020).

I argue that these dynamics cannot be fully explained by existing sustainability transitions frameworks alone. While transitions research offers robust accounts of regime-level lock-in and structural resistance to change, it remains limited in its ability to explain how everyday practices are reproduced, adapted, or selectively de-stabilized over time. In particular, transitions research has struggled to account for the micro-level processes through which practices become routinized, or fail to do so, under conditions of uncertainty, delayed feedback, and institutional constraint (Fuenfschilling & Truffer, 2014; Geels, 2020). Although recent work has called for greater engagement with practices, such efforts often treat practices as relatively stable units or carriers of change, rather than as evolving patterns of action whose durability must be continuously accomplished (Van Uden et al., 2024).

To address this gap, in this study I advance a routine-dynamics perspective on regenerative agriculture. Routine dynamics conceptualizes organizing as constituted through repetitive, recognizable patterns of interdependent action that are continuously enacted and modified in practice (Feldman & Pentland, 2003; Pentland et al., 2012). From this perspective, stability and change are not opposites but are co-produced through ongoing performances that reproduce patterns while allowing for variation and adaptation. Routine dynamics therefore offers a powerful micro-process lens for explaining how practices persist, evolve, and acquire durability over time. Still, as I argue, routine dynamics require extension to adequately capture organizing in ecological systems.

Regenerative agricultural practices are widely discussed in relation to socio-ecological systems characterized by delayed and non-linear ecological feedback, biological processes that exceed direct managerial control, and extended temporal horizons over which outcomes become visible (Duru et al., 2015; Gliessman, 2014; Tittonell, 2014). In such systems, crop growth, soil formation, climatic variability, and biological interactions shape the conditions under which patterns of action can be evaluated and potentially stabilized, often in ways that do not align with short-term decision cycles or standardized performance metrics. These characteristics pose challenges for theories of organizing that implicitly assume relatively predictable feedback, controllable material arrangements, and shorter-term action–outcome relations (Feldman & Pentland, 2003; Nicolini, 2017; Pentland & Hærem, 2015).

Recent work in organization studies has begun to question anthropocentric assumptions about action and control, emphasizing that organizing is situated, materially mediated, and embedded in relations that extend beyond human actors (Gherardi & Laasch, 2022; Nicolini, 2012; Vaujany et al., 2024). These perspectives underscore why ecological processes cannot be treated as passive contexts for action, while stopping short of explaining how patterns of action are

selectively reproduced over time under such conditions. Consequently, the problem is not a lack of sensitivity to material or ecological conditions, but the absence of processual accounts that connect such conditions to the dynamics through which routines endure, adapt, or remain fragile.

I bring these strands together by conceptualizing regenerative agriculture as a stress test for routine dynamics under socio-ecological conditions. Building on routine dynamics' process ontology, I develop an account of ecological routines as recurrent patterns of action whose reproduction depends on ongoing interaction with biological processes and ecological feedback. From this perspective, regenerative agriculture is approached not as a set of alternative techniques or managerial choices, but as a form of organizing in which patterned action must continuously align with living systems operating on temporal and material logics that exceed direct human control.

At the same time, I situate these routines within the regime-level institutional logic emphasized in sustainability transitions research. Incumbent agricultural regimes privilege standardization, predictability, and scale through established institutional, organizational, and material arrangements (Fuenfschilling & Truffer, 2014; Geels, 2002, 2019). Rather than treating regimes as abstract contexts, my analysis shows how such logic operates through everyday routines, systematically favoring the reproduction of conventional patterns of action while constraining the stabilization of ecological ones. In doing so, I link micro-level routine dynamics to macro-level regime persistence without collapsing one into the other.

By advancing a socio-ecological account of routine dynamics, I contribute to two bodies of literature. I extend routine dynamics theory by conceptualizing routines as ecological accomplishments whose reproduction depends on more-than-human components. And I also contribute to sustainability transitions research by providing a micro-process explanation for persistent patterns of partial change, showing how regime-level institutional arrangements operate through routine reproduction rather than abstract system dynamics.

1.2. Theoretical Background: Routine Dynamics beyond Human-Centric Assumptions

This section positions routine dynamics as the primary theoretical lens for analyzing regenerative agriculture, while clarifying the limits of existing accounts when organizing unfolds under ecological conditions. Rather than applying routine dynamics as a ready-made framework to a new empirical domain, the section develops the conceptual grounding needed to explain why a theoretical extension becomes necessary when routines are enacted in interaction with living systems characterized by delayed feedback, temporal autonomy, and ecological responsiveness. It begins by outlining routine dynamics as a process-oriented account of patterned action, emphasizing how routines are reproduced through ongoing performance rather than formal prescription (Section 1.2.1). It then examines how sociomaterial extensions of routine dynamics remain insufficient for capturing organizing in ecological systems, motivating a more-than-human specification of routine dynamics (Section 1.2.2). Finally, the section situates routine reproduction within broader socio-technical and institutional contexts, drawing on sustainability transitions research to frame regimes as embedded logics that shape which routines are stabilized or constrained over time (Section 1.2.3). Together, these arguments establish the analytical lenses through which regenerative agriculture and routine selection and reproduction are examined in the empirical analysis that follows.

1.2.1 Organizational Routines as Generative Patterns of Action

Routine dynamics scholarship reconceptualizes organizational routines as neither fixed rules nor habitual behaviors, but as repetitive, recognizable patterns of interdependent action carried out by multiple actors (Feldman & Pentland, 2003; Pentland & Feldman, 2005). This definition foregrounds action rather than prescription and shifts analytical attention away from routines as static entities toward routines as ongoing accomplishments enacted in practice, rather than objects that exist independently of performance (Feldman et al., 2016; Feldman & Pentland, 2003). Importantly, repetition does not imply identical replication as routines persist through recurrent enactment across varying situations, such that stability emerges as an empirical outcome of performance rather than an ontological assumption built into the routine itself (Feldman & Pentland, 2003; Howard-Grenville, 2005). Treating routines as a unit of analysis therefore requires examining how patterns of action are produced and reproduced through performance, rather than inferring routines solely from formal rules, standard operating procedures, or managerial intent (Pentland & Feldman, 2005; Pentland & Hærem, 2015).

A foundational contribution of routine dynamics is the distinction between the ostensive and performative aspects of routines (Feldman & Pentland, 2003). The ostensive aspect refers to the abstract, generalized understanding of what a routine is, while the performative aspect consists of the concrete actions taken by specific actors in specific situations (Feldman & Pentland, 2003; Pentland & Feldman, 2005). These aspects are mutually constitutive as ostensive understandings guide performance, yet performances continually modify and reproduce ostensive patterns over time (Feldman et al., 2016; Feldman & Pentland, 2003). This recursive relationship explains how routines can generate change endogenously, without requiring exogenous shocks or deliberate redesign (Feldman, 2000; Feldman & Pentland, 2003). Even when actors aim to reproduce existing patterns, situated action introduces variation that may, over time, be retained and incorporated into the routine itself, making routines a source of continuous change rather than mere inertia (Feldman, 2000; Pentland et al., 2012).

From a routine dynamics perspective, durability is not equivalent to rigidity but is instead an ongoing achievement accomplished through continued performance rather than structural inertia (Feldman et al., 2016; Feldman & Pentland, 2003). Empirical work demonstrates that routines can remain recognizable over long periods even as actors flexibly adapt actions in response to shifting organizational conditions (Howard-Grenville, 2005; Sailer et al., 2024). Persistence, in this sense, depends on the continuous effort of participants who negotiate alignment between established patterns and situational demands rather than simply reproducing fixed scripts (Feldman & Pentland, 2003; Howard-Grenville, 2005; Sailer et al., 2024). This insight reinforces the view that stability is provisional and actively maintained, rather than passively inherited from past practice (Feldman et al., 2016). Routines therefore appear stable only "for now," with their durability contingent on the sustained reproduction of patterns through performance under changing conditions (Feldman et al., 2016; Pentland & Feldman, 2005).

Conceptualizing routines as patterns of action clarifies how order is produced without assuming uniform compliance or strict adherence to scripts (Feldman & Pentland, 2003; Pentland & Hærem, 2015). Patterns emerge from recurrent sequences of interdependent actions and are observable at the level of performance rather than inferred solely from abstract descriptions or formal rules (Pentland & Feldman, 2005; Pentland & Hærem, 2015). This view aligns formal models that conceptualize routines as generative systems, i.e., structured spaces of possible action paths in which variation, selection, and retention operate endogenously (Pentland et al., 2012). Generativity does not require deliberate redesign or reflexive intent, rather, small variations

introduced through performance can accumulate and reshape patterns over time, enabling both persistence and transformation within routine dynamics (Feldman et al., 2016; Pentland et al., 2012; Sailer et al., 2024).

Routine reproduction, from this perspective, is better understood as re-enactment rather than replication, insofar as routines persist through repeated performance rather than through the faithful copying of fixed scripts (Feldman & Pentland, 2003; Pentland et al., 2012). Because routines are enacted in situated contexts, reproducing a recognizable pattern often requires variation in action rather than exact repetition, as actors adapt performances to local circumstances while maintaining overall coherence (Feldman & Pentland, 2003; Howard-Grenville, 2005). Over time, this process links synchronic variation to diachronic stability, allowing routines to persist while remaining responsive to contextual differences (Pentland et al., 2012). Syntheses of routine dynamics emphasize that routines are temporally unfolding phenomena whose apparent stability masks ongoing adjustment and coordination work across performances (Feldman et al., 2016). What appears as sameness at the level of outcomes may thus conceal substantial diversity at the level of action, reinforcing the view that reproduction is an active, effortful process rather than automatic repetition (Feldman et al., 2016; Pentland & Feldman, 2005).

While routine dynamics provides a robust account of how routines are reproduced through performance, much of this literature implicitly assumes conditions under which feedback is legible, temporal horizons are manageable, and the consequences of action remain sufficiently aligned with observed outcomes to support learning and stabilization (Feldman et al., 2016; Pentland et al., 2012). Under such conditions, variation introduced through performance can be selectively retained in ways that sustain recognizable patterns over time (Feldman & Pentland, 2003; Pentland et al., 2012). However, as I argue here, when these assumptions are strained, such as when feedback is delayed, indirect, or unevenly distributed, the mechanisms that ordinarily support routine reproduction may become less reliable, as alignment between action, feedback, and outcome becomes more difficult to sustain. Recognizing these limits does not undermine routine dynamics as a theoretical framework but instead highlights the need to specify the conditions under which routine reproduction depends on temporally distributed, indirect, and place-specific forms of feedback.

1.2.2 From Sociomaterial to More-than-Human Routine Dynamics

Routine dynamics has shifted attention from routines as fixed entities to routines as ongoing accomplishments. In that trajectory, the "material turn" is best read as an internal development rather than an external critique as scholars increasingly treat routines as enacted in and inseparable from sociomaterial contexts, where objects and other actants participate in shaping action (D'Adderio, 2011; Feldman et al., 2016). Artefacts and technologies do not merely support routines; they can mediate coordination, "make explicit or hide" actions and viewpoints, and thereby render connections between practices and outcomes more or less visible (D'Adderio, 2011; Feldman et al., 2016).

Artefacts, tools, documents, technologies, and infrastructures are already treated within routine dynamics as constitutive participants in performance, not as an external "context" that merely surrounds action (D'Adderio, 2008, 2011; Leonardi, 2011). They coordinate and sequence activity by distributing cognition and calculation, and by functioning as mediators that participate in the co-creation of knowledge and the transformation of action rather than serving as passive intermediaries (D'Adderio, 2011; Leonardi, 2011). Through inscription, artefacts can carry scripts,

rules, and assumptions forward, shaping what becomes repeatable and recognizable in subsequent performances (D'Adderio, 2011; Leonardi, 2011). In transfer and reproduction, routines are enacted through specific configurations of artefacts and communities that shape ostensive and action patterns over time, supporting durability while leaving outcomes continuously contingent on the sociomaterial ensemble being performed (D'Adderio, 2014).

Sociomaterial perspectives in routine dynamics draw on insights from science and technology studies and actor–network theory (ANT), particularly their rejection of strict human–material dualisms and their emphasis on relational, enacted agency (Latour, 2005; Orlikowski, 2007; Sele, 2021). Rather than adopting ANT wholesale, routine dynamics mobilizes these insights pragmatically to foreground how agency emerges through action and association in practice, while retaining an analytical focus on routine performance and reproduction (Latour, 2005; Sele, 2021).

I argue that despite these advances, sociomaterial routine dynamics encounters systematic limits when extended to ecological settings. The material elements typically theorized in routine studies, e.g., artefacts, technologies, documents, and infrastructures, are largely designed, engineered, and standardized, embedding scripts and purposes oriented toward human use and organizational legibility (D'Adderio, 2011; Leonardi, 2011). Such material arrangements support the reproducibility of routines by stabilizing action sequences and enabling relatively legible feedback loops that allow actors to recognize, evaluate, and adjust performances over time (D'Adderio, 2014; Feldman et al., 2016). Ecological systems cannot be treated as "just another materiality" within routine dynamics. Unlike artefacts or technologies, ecological actors are living, generative, and patterned by autonomous temporal rhythms (seasonal, cyclical, and often non-linear) that unfold independently of organizational intent (Nadegger & Wegerer, 2024).

These dynamics introduce delayed, indirect, and frequently ambiguous feedback, as well as forms of stabilization that are partial, provisional, and reversible rather than cumulative or durable (Sele & Grand, 2016; S. M. Xu & Carlile, 2024). As a result, routines in ecological settings are enacted with ecological systems, not merely supported by them. Agency in such contexts remains relational and distributed but cannot be reduced to material affordances or scripts; it is exercised through ongoing mutual adjustment between human action and more-than-human processes (Gherardi & Laasch, 2022). Still, recognizing routines as enacted with temporally autonomous ecological systems also raises questions about how such routines are enabled, constrained, or selected within wider socio-technical and institutional logics.

1.2.3 Sustainability Transitions as a Macro-Context for Routine Reproduction

Building on this understanding of routines as enacted with temporally autonomous ecological systems, a further analytical step concerns the conditions under which such routines are reproduced and stabilized beyond local performance. Routine dynamics has demonstrated that persistence depends on recurrent enactment, selective retention of variation, and the alignment of action with observable outcomes over time (Feldman & Pentland, 2003, 2022; Howard-Grenville, 2005; Pentland et al., 2012). However, these mechanisms operate within broader environments that shape which forms of variation are recognized, sustained, or rendered viable. When feedback is indirect, delayed, or unevenly distributed, as is often the case in ecological settings, the reproduction of routines cannot be explained solely at the level of situated action. Instead, attention must also be paid to the wider institutional, infrastructural, and socio-technical conditions that systematically enable some routines to stabilize while constraining others (Feldman & Pentland, 2022; J. Köhler et al., 2019; S. M. Xu & Carlile, 2024).

Sustainability transitions research is centrally concerned with the persistence and transformation of socio-technical systems, emphasizing how stability is reproduced through regimes that structure technologies, practices, infrastructures, markets, and institutions over extended periods (Geels, 2002, 2020; J. H. Köhler et al., 2025; Markard et al., 2012). Within this literature, regimes are not treated as strategic or intentional actors, but as relatively coherent configurations that stabilize dominant ways of producing and organizing societal functions by shaping selection pressures and paths of development (Geels, 2010; J. Köhler et al., 2019). From this perspective, regime stability arises less from coordinated action than from patterned alignment across multiple system elements, which privileges certain forms of practice while rendering alternatives costly, marginal, or difficult to sustain. Read through a routine dynamics lens, regimes can thus be understood as structured institutional environments that condition which routines are more likely to be reproduced or abandoned over time. This translation preserves the macro-structural insight of transitions research while retaining an explicitly micro-processual focus on routine enactment and stabilization (Geels, 2020; Van Uden et al., 2024).

Therefore, I use sustainability transitions in this study in a deliberately selective way. Rather than theorizing transition pathways, niche emergence, or regime change dynamics, my analysis draws on transitions research to specify the institutional logic within which routines are reproduced or de-selected. Routine dynamics remains the primary explanatory framework, while sustainability transitions serves as a contextual lens for identifying the regime-level conditions that systematically shape these processes. In the analysis that follows I examine how such regime-level logic operates in practice, focusing on how regenerative agriculture, as an emerging niche, encounters patterned constraints and opportunities that shape the stabilization and reproduction of novel farming practices across institutional, infrastructural, financial, and epistemic domains.

1.3 Methods

1.3.1 Empirical Setting: Regenerative Agriculture as Ecologically Embedded Practice

This study is situated in the empirical setting of regenerative agriculture, which is currently marked by ongoing contestation regarding its definitional boundaries, criteria, and normative commitments (Newton et al., 2020). Given this variability, this study treats regenerative agriculture not as a fixed or uniform model, but as an empirical field in which farming activity is oriented around ecological processes such as soil function, nutrient cycling, water dynamics, and biodiversity interactions (Lal, 2020; Schreefel et al., 2020; Sherwood & Uphoff, 2000). Across this field, a recurring orientation is the emphasis on soil as a foundational medium of production and resilience, with attention to rebuilding soil structure, biological activity, biodiversity, and organic matter through sustained management (Montgomery et al., 2022; Schreefel et al., 2020).

Empirical research on regenerative and closely related diversified farming systems indicates that ecological outcomes (e.g., improved soil properties, water retention, or system resilience) often emerge through interactions among multiple practices and biophysical processes over time, rather than through isolated interventions (Fenster et al., 2021; Montgomery et al., 2022; Schreefel et al., 2020). Studies also show that the effects and viability of these practices are strongly conditioned by local soils, climate, and landscape features, with performance varying across sites and seasons (Deng et al., 2022; Passinato et al., 2021; N. Xu et al., 2022). As a result, farming practices frequently require iterative adjustment, with timing, intensity, and combinations modified in response to observed ecological feedback and seasonal variability (Gosnell et al.,

2020; Luján Soto et al., 2021). This adaptive character is especially evident in regenerative grazing and integrated systems, where outcomes depend on ongoing plant–soil–animal interactions and responses to shifting vegetation and moisture dynamics over time (Rowntree et al., 2020; Teague et al., 2016).

Accordingly, regenerative agriculture constitutes an empirical setting in which farming practices are enacted and recalibrated in close relation to ecological conditions, temporal lags, and feedback effects that resist standardization across contexts (Deng et al., 2022; Teague et al., 2016). This ecological embeddedness and the repeated need for adjustment form the empirical backdrop for the analysis developed in the results section that follow.

1.3.2 Data and Analytical Approach

I draw on 48 semi-structured interviews conducted with actors involved in regenerative agriculture, including growers, consultants, extension agents, funders, agribusinesses, certifiers, academics, and policy experts. Growers constitute the largest group of interviewees (Table 1). Most interviews were conducted in California, with additional participants operating in other U.S. regions included to identify whether any salient differences in the dynamics described emerged across regional contexts.

Table 1: Interviewee distribution by actor category.

Actor category	Role in the field	N
Farmers	On-farm practice and ecological routine performance	22
Consultants	Advisory support and practice translation	5
Extension agencies	Knowledge dissemination and technical assistance	5
Academics	Research and conceptual framing	3
Food businesses	Supply chain coordination and market interface	3
Funding agencies	Capital provision and program design	3
Certifiers	Standards development and verification	2
Finance	Lending and risk assessment	2
Policy experts	Regulatory and policy analysis	2
Agronomy businesses	Product commercialization and technical services	1
Total		**48**

I oriented interviews toward participants' experiences with sustainability transitions, focusing on institutional conditions, organizational arrangements, perceived barriers and enablers, and the challenges of adopting and sustaining regenerative practices over time. While interviews were not initially designed to elicit detailed accounts of everyday practice, participants frequently described how practices were developed, adjusted, and maintained in response to ecological, organizational, and institutional constraints. These accounts provided empirical material for examining patterns of action in contexts characterized by uncertainty. I therefore focused the analysis on routine dynamics and reproduction conditions, such as formation, stabilization,

learning, and breakdown pressures, rather than on reconstructing complete sequences of routine performance. This approach allows theorizing processes of routinization under ecological conditions without presuming direct observation of every routine instance.

In addition to interviews, I conducted participant observations at 17 regenerative agriculture–related events, totaling over 100 hours. These observations focused on workshops, conferences, and convenings rather than continuous day-to-day farm operations, and served to contextualize interview accounts by capturing how practices, challenges, and knowledge were collectively discussed and interpreted across the field.

I followed an abductive approach to data analysis (Timmermans & Tavory, 2012), involving iterative movement between empirical material and theoretical concepts. Constructivist grounded theory principles (Charmaz, 2014) guided coding and theory development. I kept initial coding close to participants' accounts of transition processes, institutional conditions, and practical challenges. Through focused coding, recurring patterns related to routine formation, stabilization, learning, and breakdown became analytically salient, which led me to use routine dynamics as a central interpretive framework.

Throughout the analysis, I treated themes such as mindset, identity, incentives, and outcomes as contextual conditions or consequences rather than primary explanatory mechanisms. This analytical choice reflects the study's focus on routines as patterns of action reproduced through performance and interaction with ecological and institutional environments, rather than on individual motivations or attitudinal change.

1.4 Findings: Ecological Routines in Regenerative Agriculture

Here I develop the concept of ecological routines as a way of theorizing how regenerative agricultural practices stabilize through ongoing interaction with ecological processes and institutional conditions. Unlike the dominant agricultural system, also referred to as conventional agriculture, in which stability is often achieved through standardized input regimes, regenerative agriculture relies on interdependent biological feedback and system-level coupling, rendering patterns of action more context-dependent, temporally extended, and uncertain. Figure 1 summarizes the conceptual architecture emerging from the analysis. It illustrates how ecological routines are reproduced through the interaction between a regenerative system logic characterized by closed-loop ecological dependencies and structural context-dependence, the routine dynamics through which routines are enacted and stabilized in practice, and a conventional system logic that systematically privileges standardization, predictability, and scalability across institutional domains. The sections that follow examine each of these dimensions in turn.

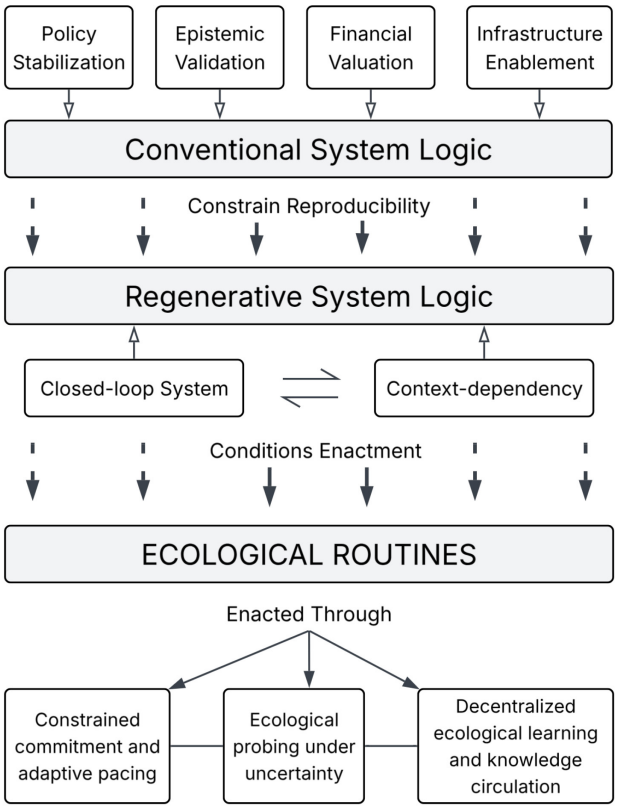


Figure 1: Conceptual architecture of ecological routines in regenerative agriculture.

1.4.1 Regenerative System Logic: Context-Dependent, Closed-Loop Ecological Routine System

I identify a regenerative system logic that conditions how patterned action can emerge and persist in regenerative agriculture. Rather than operating through linear interventions or independently adjustable practices, regenerative systems are organized around ecological interdependencies that bind action to biological feedback and place-specific conditions. This system's logic establishes the conditions under which routines can form at all in this setting. Table 2 summarizes the core mechanisms through which this logic operates, distinguishing between closed-loop ecological dependencies and context-dependence as structural properties of action.

Table 2: Regenerative system logic of regenerative agriculture.

System dimension	Mechanism	Analytical role	Exemplary empirical anchor
Closed-loop dependency	Cross-domain feedback	Ecological practices/processes operate in synergy	"Once we stacked compost and grazing together, we saw a bigger boost than doing them separately." "[we] offer the plant […] a salad bar […] the plant feeds the carbohydrates from photosynthesis back to the soil microbes. So a symbiotic relationship."

System dimension	Mechanism	Analytical role	Exemplary empirical anchor
	Temporal lag	Outcomes materialize according to ecological cycles	"It takes time to build biology […] this isn't something you see right away." "Managing in a way that is very adaptive [to] how things are changing in a given season."
Context-dependence	Non-transferability	Practices cannot be directly replicated across sites	"What works here wouldn't work in Texas." "There will be different kinds. I think that that's part of the context […] it's like figuring out what works for you."
	Situated calibration	Ongoing local adjustment is required	"There's no recipe, you have to figure out what works for your land." "The key is learning how to work with changes […] in a way that doesn't, hinder […] increasing biodiversity"

Regenerative agriculture operates through closed-loop ecological dependencies in which routine performance is co-produced through ongoing interaction between human action and biological processes. Soil function, vegetation dynamics, water availability, and microbial activity are interdependent and responsive, such that interventions in one domain actively reshape conditions in others. Causality in this system is therefore distributed and temporally extended: outcomes emerge through cumulative ecological responses rather than as immediate effects of managerial decisions. Because biological processes operate on their own temporal rhythms and through feedback that cannot be fully controlled or accelerated, patterned action cannot be stabilized through fixed scripts or standardized inputs without undermining system performance. Stability, where it occurs, is contingent on sustained alignment with ecological responses rather than on procedural replication.

At the same time, routine performance is structurally inseparable from place, as ecological processes respond differently to intervention depending on locally specific configurations shaped by climate, soils, hydrology, and prior land-use trajectories. Context-dependence therefore reflects not passive variation but active ecological differentiation, in which local dynamics condition what forms of action can persist and with what effects. Practices cannot be abstracted from these configurations and reapplied without recalibration, because ecological systems themselves participate in shaping outcomes as they respond to management over time. What stabilizes across contexts is thus not the uniform content of action, but a logic of ongoing adjustment to locally situated ecological change. Altogether, closed-loop dependency and context-dependence establish why patterned action in regenerative agriculture must be understood as emerging within a system in which more-than-human processes are constitutive of routine performance rather than external to it.

1.4.2 Core Routine Dynamics of Ecological Routines

Within the system logic established in Section 1.4.1, I show that patterned action in regenerative agriculture stabilizes through identifiable routine dynamics rather than through the replication of standardized practices. These dynamics explain how ecological routines, understood as recurrent patterns of action co-produced through ongoing interaction between human actors and

more-than-human processes, form, persist, and reproduce under conditions of ecological uncertainty, delayed feedback, and ecologically differentiated system responses. Table 3 summarizes the core mechanisms through which these routine dynamics operate.

Table 3: Core routine dynamics of ecological routines.

Core routine dynamic	Mechanism	Analytical role	Exemplary empirical anchor
Ecological probing under uncertainty	Iterative probing	Enables routine emergence in the absence of preexisting knowledge	"The playbook has not been written." "It's a lot of mindset figuring out."
	Practice experimentation	Generates system-level ecological feedback through experimentation	"Trying different arrangements of cover crops and different timing in the irrigation and just lots of experimenting." "I call it an experimental farm."
Constrained commitment and adaptive pacing	Constrained commitment	Limits exposure to ecological and operational risk while feedback becomes legible	"Try it on a couple acres—don't bet the farm." "We were really surprised at how much […] that section improved […] So we decided to double that experiment."
	Selective retention	Stabilizes routines without fixing final practice configurations	"We expanded only after we saw it work again." "We've tried small areas, you know, one field, this and another field, we do this."
Decentralized ecological learning and knowledge circulation	Embedded self-teaching	Sustains routine performance through continual situated learning	"We have to lean on books, podcasts and speakers […] to give us context." "I'm not finding a lot of answers from a lot of people."
	Decentralized circulation	Reproduces routines through bottom-up knowledge diffusion in the absence of formal institutions	"Farmers [are] sharing information and experience themselves." "The founder of our company tries to educate [farmers] on his podcast."

Ecological routines are sustained through experimentation because action unfolds within living systems whose responses cannot be fully anticipated, controlled, or standardized in advance. In regenerative agriculture, routine formation does not precede ecological uncertainty, instead it is constituted through ongoing engagement with it. Iterative probing and practice experimentation allow actors to work with soils, plants, water, and biological activity as responsive elements that actively shape the effects of intervention. Experimentation thus functions as a routine-forming mechanism by stabilizing ways of engaging with ecological feedback rather than by converging on predetermined solutions.

Crucially, ecological processes do not merely condition human experimentation, they participate in shaping what forms of action become viable over time. Because biological responses emerge through delayed and nonlinear interactions, repetition does not eliminate indeterminacy. Instead, experimentation becomes a patterned mode of organizing action with ecological systems whose dynamics continue to unfold. Experimental routine formation therefore explains how routines can emerge without scripts, by stabilizing engagement with ecological responsiveness rather than controlling it.

Although ecological routines remain viable through experimentation, stabilization occurs alongside and through incremental and constrained commitment. Stabilization occurs as ecological responses become sufficiently legible to support continued engagement, not as outcomes become predictable or uniform. By limiting the scale and pace of intervention, human actors allow soils, vegetation, and biological processes to respond without being overwhelmed, enabling routines to persist without disrupting system coherence.

What stabilizes through this process is not the final configuration of practices but a patterned way of pacing change. Starting small, observing ecological responses, adjusting scope, and selectively expanding become repeatable sequences of action even as material practices remain open to modification. Incremental stabilization thus reflects the temporal and responsive character of ecological systems, i.e., routines endure by remaining aligned with ongoing ecological change rather than by fixing practices into standardized forms.

Ecological routines depend on learning arrangements capable of supporting continual recalibration in the absence of standardized, regime-aligned expertise. Because ecological routines are co-produced with place-specific ecological processes, knowledge cannot be fully externalized or front-loaded. Instead, self-directed learning becomes routinized as part of everyday practice, embedded in observation, experimentation, and ongoing interpretation of ecological feedback.

Decentralized ecological learning stabilizes through distributed and informal infrastructures that circulate experience and interpretation across farming communities. In the absence of coordinated institutional support, farmers rely on peer exchange, self-education, and intermediary platforms to interpret ecological responses and adjust routines accordingly. Ecological systems continue to respond in differentiated ways across sites, making learning an enduring requirement rather than a transitional phase. Routinized learning thus enables ecological routines to be reproduced over time by embedding responsiveness to ecological processes within the routine itself.

Together, these dynamics operate simultaneously to enable the ongoing formation, stabilization, and reproduction of ecological routines, while also clarifying why their reproduction remains fragile as they are enacted within institutional conditions structured by regime-level conditions expressed through a conventional system logic.

1.4.3 Conventional System Logic

Ecological routines, while capable of formation and persistence through the dynamics outlined above, remain unevenly reproduced beyond localized contexts. This unevenness is not explained by their agronomic viability alone, but by the institutional conditions under which they are enacted. Across domains, routine reproduction depends on alignment with established ways of organizing knowledge, risk, value, and material support. Where such alignment is absent, ecological routines encounter persistent difficulties in recognition, protection, financing, and implementation.

These conditions are structured within a regime logic that organizes agricultural activity around standardization, predictability, and scale through established institutional arrangements. In contemporary agriculture, this logic is expressed through the conventional production model, which provides the dominant configuration through which such arrangements are stabilized and reproduced. I refer to this configuration here as conventional system logic. Ecological routines, by contrast, depend on context-specific adaptation, extended temporal feedback, and ongoing coordination with more-than-human processes, making them only partially compatible with these prevailing arrangements.

1.4.3.1 Epistemic Validation under Conventional System Logic

The reproduction of agricultural routines depends on how knowledge is produced, validated, and circulated within dominant agronomic systems. Under the conventional system logic, epistemic authority is anchored in forms of knowledge that are codified, transferable, and aligned with standardized production models. In regenerative agriculture, however, routine performance depends on knowledge generated through sustained engagement with soils, plants, animals, and other more-than-human processes. These forms of knowing are place-specific, cumulative, and responsive to ecological variation, making them difficult to validate and legitimize within prevailing epistemic structures (Table 4).

Table 4: Epistemic Validation and Knowledge Selection under Conventional System Logic.

Mechanism	What is privileged	What is de-selected	Exemplary empirical quote
Standardized epistemic validation	Codified, transferable agronomic knowledge aligned with input-intensive systems	Experiential, system-integrative ecological knowledge emerging through practice	"People who just graduated from the university with a degree in ag… say, you can't finish a cow on grass." "I haven't really found a good source of information in terms of how all of that integrative system."
Fragmented and misaligned knowledge infrastructures	Traditional input-model reproduction through mainstream educational institutions	Cumulative, context-dependent learning required for ecological routine performance	"There's not a good assimilation of information… there's no good hub of information." "Those are the things we need, the education and technical capacity building on the ground to help farmers."

Epistemic validation under the conventional system logic is based on forms of knowledge that can be abstracted from specific contexts and applied across standardized production environments. Dominant agronomic systems therefore privilege codified expertise aligned with input-intensive models, reinforcing assumptions that farming can be managed through controllable variables and generalized prescriptions. In contrast, ecological routines depend on knowledge that emerges through iterative engagement with ecological dynamics and cannot be readily separated

from the conditions in which it is produced. As a result, such knowledge remains difficult to validate, circulate, and legitimize within prevailing systems of agronomic expertise.

These dynamics are further reinforced by the organization of knowledge infrastructures. Agricultural education, extension, and technical assistance systems are structured to support the dissemination of standardized practices, rather than the cumulative, context-dependent learning required for ecological routine performance. As a result, knowledge integration is displaced onto individual practitioners, who must rely on self-education, peer exchange, and experimentation to interpret ecological feedback. The limitation, therefore, is not simply the absence of information, but the structuring of epistemic infrastructures around forms of validation that do not accommodate ecological modes of knowing.

1.4.3.2 Policy Stabilization of Conventional Production Models

Policy frameworks play a central role in determining which agricultural practices can persist over time by shaping how uncertainty is managed and absorbed. Under the conventional system logic, instruments such as subsidies and insurance programs stabilize production by favoring standardized and predictable farming models. Routines that rely on diversification, adaptive timing, and ecological responsiveness encounter difficulty aligning with these policy-recognized forms of stability (Table 5). This creates a structural asymmetry in which ecological routine reproduction remains dependent on forms of adaptation that existing policy architectures do not readily recognize or protect.

Table 5: Policy Stabilization and Risk Governance under Conventional System Logic.

Mechanism	What is privileged	What is de-selected	Exemplary empirical quote
Subsidy structures oriented toward standardized production	Commodity-specific, monocultural routines stabilized through income support	Diversified, non-standard ecological routines	"All subsidies are to the big crops, and I have 160 different crops on my farm." "We subsidize these large monoculture specific farms."
Risk governance through insurance support	Monoculture and standardized management regimes	Experimental, adaptive routines based on diversification	"You're basically forced to keep it mono-cropped if you want insurance." "Our crop insurance system […] is disincentivizing transition to regenerate."

This asymmetry is evident in subsidy structures that concentrate support around commodity-specific production systems. By stabilizing monocultural and input-intensive routines through income support, subsidies decouple production continuity from ecological performance, allowing conventional routines to persist even under conditions of environmental stress. Ecological routines, which rely on diversified cropping systems and biological interaction, fall outside these categories and therefore remain comparatively unsupported. As a result, diversification, while agronomically viable, becomes economically exposed, constraining its reproduction over time relative to subsidized alternatives.

A similar dynamic operates through insurance frameworks that define which forms of agricultural variability are recognized as acceptable risk. Crop insurance systems are calibrated

around standardized production models, implicitly assuming that variability should be minimized and controlled. Ecological routines, however, generate variability as part of their adaptive engagement with soils, crops, and climatic conditions. This variability is not incidental, but constitutive of ecological routine performance, yet within existing policy frameworks it is treated as financial risk rather than as a necessary condition of system adaptation. Farmers adopting regenerative practices must therefore absorb greater uncertainty during transition, slowing routine reproduction and reinforcing the relative stability of regime-aligned practices. As a result, ecological routines remain systematically exposed to risk, limiting their stabilization relative to policy-aligned conventional production systems.

1.4.3.3 Financial Valuation under Conventional System Logic

Financial valuation under the conventional system logic defines which forms of agricultural activity are recognizable as viable investments. Mainstream financial regimes privilege predictability, short-term returns, and standardized performance metrics, placing ecological routines at a structural disadvantage. Ecological routines depend on extended and uncertain time horizons, transitional variability, and ecological recovery processes whose benefits unfold unevenly and are seldom captured by financial structures, such as soil health regeneration. This positions financial systems as structuring conditions that privilege routines compatible with existing valuation frameworks while systematically de-selecting routines that remain responsive to ecological dynamics (Table 6).

Table 6: Policy Stabilization and Risk Governance under Conventional System Logic.

Mechanism	What is privileged	What is de-selected	Exemplary empirical quote
Conventional valuation and underwriting logics	Stable yield trajectories, predictable payback periods, and standardized operating models	Transitional ecological recovery, unpredictable yield trajectory, and adaptive routine development	"Conventional bankers do not understand what that transition looks like. They see it just as risk, risk, risk." "If the loans incentivized and approved [RA] practices, growers would jump."
Capital access and intermediary absence	Expansion-ready operations aligned with conventional growth models	Incremental, place-bound reproduction of ecological routines	"Larger scale capital can't invest right now in [RA] system […] there aren't mechanisms" "Access to capital for farmers […] either have subpar financing or no financing whatsoever."

This tension is most visible in valuation and underwriting practices. Financial assessments are calibrated to production systems in which outcomes can be projected, stabilized, and compared across standardized metrics. During regenerative transition, however, productivity is actively reshaped by ecological processes such as soil regeneration, biodiversity recovery, and changing input dependencies. These processes introduce variability and temporal lag that are not easily accommodated within conventional financial models. Rather than being recognized as integral to

system transformation, such dynamics are interpreted as heightened uncertainty, leading financial institutions to discount or reject ecological routines as viable investments. In this way, financial evaluation frameworks privilege routines that minimize exposure to more-than-human variability while disadvantaging those that engage it as a condition of ongoing performance.

A related constraint arises from the limited availability of capital structures capable of supporting ecological routine development beyond localized or early-stage contexts. Where regenerative agriculture secures financial support, it often relies on mission-aligned actors willing to accommodate uncertainty and longer return horizons. While such arrangements enable initial experimentation, they do not translate into broadly accessible financing pathways. As operations attempt to expand, ecological routines encounter a structural bottleneck that dominant financial architectures lack instruments and intermediaries designed to accommodate incremental scaling, adaptive management, and context-specific performance. Access to capital thus becomes conditional on alignment with established financial expectations, constraining the wider reproduction and circulation of ecological routines.

1.4.3.4 Infrastructural Enablement under Conventional System Logic

The material organization of agriculture determines what forms of practice can be carried out efficiently, at scale, and with institutional support. Existing agricultural infrastructures, from machinery design to service networks, are built around standardized, input-intensive production systems. Therefore, ecological routines, which rely on diversification, adaptive coordination, and context-specific management, encounter practical limitations in their execution within these established material arrangements (Table 7). As a result, infrastructure operates as an enabling condition for conventional production while leaving ecological routines materially under-supported.

Table 7: Infrastructural Enablement of Standardized Production Systems under Conventional System Logic.

Mechanism	What is privileged	What is de-selected	Exemplary empirical quote
Machinery and equipment alignment with standardized production	Uniform- and conventional-oriented routines aligned with monocropping and standardized field configurations	Diversified routines requiring specialized or non-standard equipment configurations	“a lot of things like machinery […] is kind of geared towards these really big scale, conventional operations.” “It's a huge hurdle for us as small farmers to invent and manufacture it [weed removal]. I don't know why it doesn't exist.”
Limited regenerative-aligned service and labor ecosystems	Input-intensive systems supported by established equipment service and labor infrastructures	Ecological routines requiring specialized skills and locally developed problem-solving capacity	“We’re still a far cry away from having the enabling mechanisms that are necessary”

Mechanism	What is privileged	What is de-selected	Exemplary empirical quote
			"The social capitals are lacking […] I mean, like human resources."

Infrastructural enablement under the conventional system logic is first expressed through material lock-in embedded in machinery and equipment design. Existing agricultural technologies are geared toward uniform cropping systems, standardized field configurations, and large-scale operations, making them poorly suited for diversified and adaptive farming practices. Producers attempting to implement ecological routines frequently encounter a lack of appropriate equipment, particularly for managing diverse cropping systems, cover crops, or non-standard field arrangements. In response, farmers must either operate with suboptimal tools or invest time and resources in modifying or fabricating equipment themselves. What this reveals is not a limitation of ecological routines per se, but the extent to which material infrastructures are designed to support standardized production, leaving alternative modes of practice without equivalent technical backing.

This pattern extends to the organization of service and labor ecosystems. Conventional agricultural systems benefit from dense networks of equipment suppliers, maintenance services, and trained labor, all of which reduce the effort required to reproduce established routines. Ecological routines, by contrast, often lack access to comparable support structures. Specialized equipment is difficult to source, technical assistance remains fragmented, and labor familiar with regenerative practices is scarce. As a result, producers must internalize functions that are typically externalized in conventional systems, including equipment adaptation, troubleshooting, and operational coordination. This increases the labor intensity and complexity of ecological routine performance, limiting their reproducibility across contexts. These infrastructural arrangements thus enable the efficient reproduction of standardized production while constraining the scalability and circulation of ecological routines.

Taken together, the four domains presented here indicate that the uneven reproduction of ecological routines is not the result of isolated institutional barriers but reflects the operation of a conventional system logic that systematically structures how agricultural activity is recognized, supported, and extended. Across epistemic, policy, financial, and infrastructural domains, this logic favors forms of production that are standardized, predictable, and compatible with existing institutional arrangements, while disadvantaging those that depend on ecological responsiveness, temporal adaptation, and context-specific coordination. Ecological routines are thus not constrained through direct opposition, but through the cumulative effect of institutional conditions that render them less legible, less protected, less financeable, and less materially supported. This helps explain why regenerative practices can persist and demonstrate viability in localized settings yet struggle to achieve broader stabilization and circulation under prevailing institutional conditions structured through conventional system logic.

1.5. Discussion

In this study I theorize ecological routines as patterns of action whose performance and reproduction depend on sustained engagement with ecological feedback and the participation of more-than-human processes. Rather than treating routines as stabilized sequences enacted

primarily through human coordination and inert material supports, my findings show how routine viability in ecological contexts is continually shaped by living systems that respond, adapt, and feed back into practice performance. Under such conditions, routine persistence is not achieved through invariance or optimization, but through continuous calibration and adjustment. Ecological routines are therefore necessarily context-dependent and incrementally stabilized, with stability emerging as an ongoing accomplishment rather than a fixed state.

My findings align closely with the core commitments of routine dynamics, which conceptualizes routines as generative systems reproduced through repeated enactment rather than as fixed scripts or programs of action (Feldman & Pentland, 2003; Pentland & Feldman, 2005). From this perspective, variation is endogenous to routine reproduction rather than a deviation from it, and persistence is understood as a processual outcome produced through situated performance (Feldman et al., 2016; Feldman & Pentland, 2003). Prior research has shown how routines can remain recognizable while flexibly adapting to shifting conditions, actor orientations, and interdependent patterns of action, underscoring that change and stability are co-produced through the same generative mechanisms (Feldman & Orlikowski, 2011; Rosales et al., 2022; Sailer et al., 2024). Read in this light, the patterns observed in regenerative agriculture do not challenge routine dynamics' foundational assumptions but expose the limits of existing accounts when routine reproduction unfolds under conditions of persistent ecological variability.

Building on this alignment, I extend routine dynamics by specifying the conditions under which routine reproduction unfolds when material environments are not merely mediating or buffering variability but are themselves responsive and generative of feedback. Much of the routine dynamics literature has examined routines in organizational contexts where material arrangements can absorb, standardize, or temporally structure variability through artifacts, rules, and technological mediation (D'Adderio, 2008, 2011, 2014; Feldman et al., 2016; Turner & Rindova, 2018). In contrast, ecological routines, as observed in regenerative agriculture, operate under materially responsive conditions in which soil processes, hydrological dynamics, biotic interactions, and climatic heterogeneity continually shape what actions are viable, when they can be performed, and with what effects. These ecological processes do not direct action nor displace human agency, rather, they participate in the conditions under which routine performances unfold (Murray et al., 2021). Under such conditions, routine stabilization depends on ongoing engagement with ecological feedback rather than on standardization, input substitution, or practice replication. This distinction helps explain why regenerative routines may remain viable and meaningful at the local level while struggling to persist and circulate within institutional environments configured to privilege predictability, control, and uniformity (Feldman, 2000; Feldman & Pentland, 2022; S. M. Xu & Carlile, 2024).

The conditions that enable ecological routines to persist locally also help explain why their broader reproduction remains fragile. From this perspective, the limited stabilization of regenerative practices cannot be attributed primarily to farmer motivation, knowledge, or performance. Instead, it reflects how prevailing institutional arrangements, structured through a conventional system logic, are organized in ways that make routines incorporating ecological variability more difficult to sustain. The challenge facing regenerative agriculture is therefore not one of innovation failure, but of structural incompatibility between ecological routine reproduction and prevailing regime logics.

Classic sustainability transitions scholarship has typically conceptualized transition dynamics through distinctions between niches, regimes, and landscapes, emphasizing alignment across levels and moments of destabilization as central mechanisms of change (Geels, 2010, 2019;

J. Köhler et al., 2019). My findings suggest a complementary interpretation. Transition dynamics also unfold through policy, financial, epistemic, and infrastructural arrangements that shape how routines are sustained and extended in everyday practice. Rather than operating only through punctuated regime change, these dynamics operate continuously, stabilizing some patterns of action while rendering others more difficult to sustain. From this perspective I bring into focus the micro-level processes through which broader transition trajectories are enacted, constrained, or redirected via routine reproduction.

Recent sustainability transitions scholarship has called for stronger micro-level accounts that take everyday practices seriously as sites where change is enacted, resisted, or redirected, including explicit efforts to connect the Multi-Level Perspective with social practice approaches (Keller et al., 2022; Koistinen & Teerikangas, 2021). My findings speak directly to these calls while also complicating them. They show that transition failure can occur even when alternative practices are present, technically viable, and circulating across contexts. In the case of regenerative agriculture, the bottleneck does not lie in the absence of alternative practices, but in their reproduction under regime-favored institutional conditions. This indicates that a focus on practices alone is insufficient if the conditions that enable their ongoing reproduction remain misaligned. Understanding transition dynamics therefore requires closer attention to how routine reproduction is structured through everyday institutional arrangements that shape what forms of action can persist over time.

I make two interrelated contributions. First, I extend routine dynamics by theorizing ecological routines as patterns of action whose reproduction depends on sustained engagement with ecological feedback and the participation of more-than-human processes. By specifying how routine persistence and change unfold when outcomes are mediated by living, responsive systems, this study advances routine dynamics' processual account without presuming symmetry or displacing human agency. Ecological responsiveness is thus conceptualized not as an alternative ontology, but as a condition under which routine dynamics must operate in socio-ecological settings.

Second, I demonstrate how routine dynamics can be empirically linked to regime-level institutional environments, providing a concrete bridge between micro-level routine reproduction and broader transition dynamics. By tracing how policy, financial, epistemic, and infrastructural arrangements structure the conditions under which routines are reproduced in everyday practice, my analysis shows how institutional environments continuously shape which patterns of action can be sustained and extended over time. Together, these contributions clarify how ecologically viable routines may persist locally while remaining structurally disadvantaged under mainstream institutional arrangements.

The study also has limitations that point to productive directions for future research. Empirically, the analysis is grounded in a specific set of geographic contexts and production systems, and it focuses primarily on agricultural production rather than downstream processing, distribution, or consumption. The temporal scope captures routine formation and stabilization but cannot fully trace longer-term breakdown or reconfiguration. Future research could extend this approach through comparative analysis across ecological contexts, longitudinal tracking of routine persistence and disruption, and application to other sustainability domains in which outcomes depend on living systems, such as water governance, fisheries, or urban ecological management. Such work would further refine understanding of how ecological responsiveness reshapes routine reproduction and transition dynamics across socio-ecological settings.

Here, I have argued that regenerative agriculture is best understood not as a scalable set of techniques, but as a form of ecological routine work. Drawing on routine dynamics, the analysis showed how regenerative practices stabilize as ecological routines: recurrent patterns of action whose reproduction depends on sustained engagement with more-than-human processes, including soils, plants, animals, and climatic dynamics that respond on their own temporal rhythms. Under these conditions, routine performance unfolds through delayed and non-linear feedback, place-specific ecological differentiation, and ongoing mutual adjustment between human action and living systems. While ecological routines can form and persist through experimentation, incremental stabilization, and routinized learning, they remain structurally fragile beyond localized contexts. This fragility does not reflect technical failure or a lack of practitioner commitment, but the operation of a conventional system logic that favors routines oriented towards standardization, predictability, and control, while systematically de-selecting routines that remain responsive to ecological dynamics.

1.6 Conclusion

At a moment when climate disruption, landscape degradation, and ecological volatility are intensifying pressures for sustainability transitions in agriculture, my analysis points to where institutional change is most urgently needed. If regenerative practices endure through responsiveness, adaptation, and sustained engagement with ecological feedback, then transition efforts cannot rely primarily on scaling fixed models or codifying best practices. Instead, policies, financial arrangements, and infrastructural systems must be reoriented to support experimentation, tolerate variability, and accommodate extended ecological time horizons. Seen this way, regenerative agriculture is not a marginal or incomplete alternative, but an indicator of the kinds of institutional conditions required for organizing with living systems. This framing of regenerative agriculture as ecological routine work opens a more constructive path forward, one that shifts attention toward designing institutional environments capable of supporting the durable reproduction of ecologically viable practices under conditions of ecological change.

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CHAPTER 2: Regenerative Agriculture Without Increased Water Consumption? Evapotranspiration Dynamics in California Perennial Agriculture

Abstract

Debates surrounding regenerative agriculture increasingly center on its capacity to improve environmental performance, yet its implications for consumptive water use remain poorly understood. While a growing body of research documents improvements in soil health under regenerative management, far less is known about its implications for consumptive water use. This gap is especially consequential in water-constrained regions, where claims regarding regenerative agriculture's water-saving potential carry implications for groundwater governance and agricultural sustainability transitions. In this study, I evaluate whether regenerative management is associated with differences in consumptive water use relative to conventional systems in irrigated perennial agriculture. Using matched pairs of regenerative and conventional almond orchards and vineyards across California and field-scale evapotranspiration (ET) estimates derived from the OpenET satellite platform, I compare site-level mean ET, seasonal patterns, and within-pair variability across multiple observation windows. ET is treated as a proxy for consumptive water use because it captures the dominant atmospheric flux through which irrigation water leaves the hydrologic system. Results indicate that regenerative management does not increase consumptive water use relative to conventional systems. Statistically significant differences emerged only in almond orchards under the larger matched design (2023–2025; n = 14 pairs), where conventional systems exhibited higher ET than regenerative counterparts, particularly during peak summer months. Vineyard systems showed no consistent site-level differences across either observation window. Across crops, seasonal patterns revealed substantial overlap and variability among matched pairs, indicating that differences were heterogeneous rather than uniformly expressed. These findings challenge assumptions that regenerative practices necessarily increase water demand through greater biomass production or soil moisture retention. Instead, they suggest that regenerative systems can maintain comparable or modestly lower consumptive water use while pursuing soil health and biodiversity objectives. By directly quantifying evapotranspiration rather than inferring hydrological outcomes from soil indicators alone, this study contributes empirical evidence to ongoing debates regarding the water implications of regenerative agriculture under groundwater-constrained conditions.

2.1 Introduction

Regenerative agriculture (RA) is increasingly framed not simply as a set of alternative practices, but as a systemic reconfiguration of farming itself (Congreves, 2025; Gordon et al., 2023; Newton et al., 2020). Rather than treating soil as a passive material devoid of ecological agency, RA frames the farm as a living ecological system whose productivity emerges from the quality of relationships among soil organisms, plants, water, and human management (Lal, 2020; Rhodes, 2017). In this perspective, soil health becomes the central focus of farm management rather than just one objective among many. Brown (2018) popularizes this view by arguing that

regenerative farmers cultivate soil first while viewing thriving crops as a consequence of ecological integrity. Empirical studies further distinguish regenerative systems from conventional agriculture through reduced reliance on synthetic fertilizers and pesticides and greater emphasis on biodiversity and ecological functioning (Fenster et al., 2021; Gosnell et al., 2020; LaCanne & Lundgren, 2018; Luján Soto et al., 2021; Xu et al., 2022). Collectively, this literature portrays RA as a shift in both landscape and mindset, positioning ecological processes not as constraints to be controlled, but as productive partners in agricultural performance.

While RA is frequently presented as transformative, empirical validation has primarily been reported through measurable changes in soil health indicators (Fenster et al., 2021; Luján Soto et al., 2021; Newton et al., 2020; Xu et al., 2022). Regenerative practices such as cover cropping, reduced disturbance, organic amendments, and living mulches have been associated with improvements in soil organic matter, aggregation, biological activity, and nutrient cycling (Adamczewska-Sowińska et al., 2022; Luján Soto et al., 2021; Xu et al., 2022). In perennial and woody systems, soil restoration efforts have demonstrated gains in organic carbon stocks, aggregate stability, and infiltration capacity, particularly when organic inputs and vegetative cover are combined (Luján Soto et al., 2021). Strong empirical relationships consistently emerge between organic matter and maximum water holding capacity, cation exchange capacity, soil protein, and nitrogen availability, suggesting that soil regeneration operates through interdependent biophysical processes rather than isolated metrics (Fenster et al., 2021). Similarly, regenerative management has been shown to reduce bulk density and improve aggregate stability, thereby enhancing soil structure and resistance to erosion (Adamczewska-Sowińska et al., 2022).

However, improvements in soil structure, organic matter, and infiltration do not necessarily translate into reductions in consumptive water use. Regenerative agriculture is often assumed to reduce agricultural water demand through enhanced soil moisture retention and improved infiltration, yet these same processes can also sustain or even increase plant transpiration if improved soil conditions stimulate greater vegetative growth (Lankford & Orr, 2022). In irrigated perennial systems, transpiration constitutes a dominant component of evapotranspiration, the primary pathway through which water leaves the land surface and returns to the atmosphere (Allen et al., 1998; Fereres & Soriano, 2007).

Recent work has begun to engage this question more directly. In a limited field-scale study of five almond orchards spanning a gradient from conventional to regenerative management in California's Central Valley, Flynn et al. (2025) quantified evapotranspiration using eddy covariance and soil moisture monitoring. They observed little difference in winter evapotranspiration between management types and similar or slightly lower growing season evapotranspiration at regenerative sites, despite higher observed soil water infiltration. These findings underscored that soil moisture improvements do not mechanically determine consumptive water use and reinforce the need for systematic evaluation of evapotranspiration under contrasting management systems.

Evapotranspiration provides the most direct measure of consumptive water use in irrigated agricultural systems. Recent USGS model estimates indicate that approximately 70% to 75% of irrigation withdrawals in the United States are consumptively used, primarily through evapotranspiration (Medalie et al., 2025). As the dominant atmospheric water flux in irrigated agriculture, evapotranspiration captures the combined effects of soil moisture availability, crop physiological demand, and atmospheric conditions (Allen et al., 1998). Lankford and Orr (2022) emphasized that what matters for water accounting is not merely soil water retention but the degree to which crops approach their potential or ideal evapotranspiration under given environmental

constraints. In this sense, regenerative improvements in soil structure may either moderate or sustain transpiration, depending on how they interact with plant growth and irrigation management.

Recent advances in satellite-based evapotranspiration estimation now permit field-scale comparison of management systems with increasing reliability. The OpenET web platform uses multiple remotely sensed models to generate spatially explicit monthly evapotranspiration estimates across the United States (Melton et al., 2022). Comparative validation studies in California almond orchards demonstrate that OpenET products perform consistently across irrigated perennial systems (Knipper et al., 2024). Together, these developments enable systematic evaluation of consumptive water use under contrasting management regimes. These evaluations can now be conducted at spatial and temporal scales relevant to both farm decision-making and basin-level governance.

The question of consumptive water use under regenerative management is particularly salient in California's Central Valley, where irrigated agriculture accounts for the majority of basin-level water depletion (Wong et al., 2021). The passage of the Sustainable Groundwater Management Act (SGMA) established a landmark regulatory framework requiring local agencies to achieve groundwater sustainability through measurable reductions in overdraft, placing renewed emphasis on transparent accounting of agricultural water use (SGMA, 2014). In this policy context, assumptions regarding the water-saving potential of alternative management systems carry material implications for both farm-level decisions and basin-scale governance. In this study, I evaluated whether regenerative management is associated with differences in consumptive water use relative to conventional systems in irrigated perennial crops. Using matched pairs of regenerative and conventional almond orchards and vineyards and field-scale estimates of evapotranspiration, I examined site-level and seasonal differences in evapotranspiration across management types. By directly quantifying consumptive water use rather than inferring hydrological outcomes from soil indicators alone, I contribute with evidence to an ongoing debate regarding the water implications of regenerative agriculture in water-constrained agroecosystems.

2.2 Evapotranspiration as a Proxy of Agricultural Water Consumption

Evapotranspiration (ET) represents the combined flux of evaporation from soil and surface water and transpiration from vegetation to the atmosphere (Allen et al., 1998; Wanniarachchi & Sarukkalige, 2022). As a core component of the terrestrial water balance, ET transfers water from the land surface to the atmosphere through coupled energy and biophysical processes. In agricultural systems, transpiration is directly linked to plant physiological activity, including stomatal conductance and canopy development, and therefore reflects crop water use during growth (Allen et al., 1998). Because ET integrates soil, atmospheric, and vegetative controls, it constitutes the dominant water loss pathway in irrigated semi-arid regions (Wanniarachchi & Sarukkalige, 2022; Wong et al., 2021).

In Mediterranean climates such as California's Central Valley, precipitation is concentrated in winter months and is generally insufficient to meet crop water demand during the summer growing season (Wong et al., 2021). Irrigation compensates for seasonal soil moisture deficits, and most applied irrigation water is ultimately lost to the atmosphere through evapotranspiration rather than remaining within the basin (Wong et al., 2021). This tendency is particularly pronounced in modern high-efficiency irrigation systems, such as drip irrigation, where surface runoff and deep percolation losses are minimized (Perry et al., 2009). Consequently, seasonal ET provides a close

approximation of consumptive water use, i.e., water that leaves the hydrologic system as atmospheric flux and is no longer available for downstream reuse (Allen et al., 1998; Martin et al., 2025). In this study, ET is expressed as a depth (inches over area), representing the equivalent depth of water lost from a unit surface.

Importantly, ET does not directly measure diverted, pumped, or applied water volumes, nor does it directly reflect irrigation efficiency. Rather, it quantifies water consumed by the coupled soil–plant–atmosphere system, making it particularly relevant for basin-scale water accounting and groundwater sustainability policy (Melton et al., 2022; Wong et al., 2021). Moreover, satellite-based ET accounting carries a few limitations. ET derived from remote sensing cannot fully separate evaporation from transpiration, incurring uncertainty associated with satellite retrievals and model parameterization (Knipper et al., 2024; Melton et al., 2022).

In this study, I treat evapotranspiration as a proxy for consumptive water use and it therefore represents the effective water demand associated with regenerative and conventional management systems. This treatment enables matched comparisons of management-related differences in atmospheric water loss.

2.3 Methods

2.3.1 Study Region and Site Context

California's Central Valley is one of the most productive irrigated agricultural regions globally, extending approximately 600 km north–south. The Valley comprises the Sacramento Valley in the north and the San Joaquin Valley in the south, connected through the Sacramento–San Joaquin Delta (Faunt, 2009; Yu et al., 2025). Together, these regions account for roughly 75% of California's irrigated lands and more than 7 million irrigated acres (about 28,300 km²), supporting extensive production of perennial specialty crops, including almonds and wine grapes (Faunt, 2009; Wong et al., 2021).

The Central Valley exhibits a Mediterranean climate characterized by cool, wet winters and hot, dry summers. Mean annual precipitation ranges from approximately 510 mm yr^{-1} in the northern Valley to approximately 130 mm yr^{-1} in the southern extent, with the majority of rainfall occurring between November and March (Wong et al., 2021). This pronounced seasonal concentration of precipitation produces sustained summer soil moisture deficits, rendering perennial agriculture largely dependent on irrigation during the growing season. At the regional scale, agricultural evapotranspiration averages approximately 820 ± 290 mm yr^{-1}, with substantial spatial heterogeneity associated with crop type and local climatic conditions (Wong et al., 2021).

Irrigation water in the Central Valley is supplied through a combination of surface water conveyance systems and groundwater extraction. Groundwater contributes approximately 30% of supply in wet years and up to 70% during dry years when surface water availability is limited (Wong et al., 2021). Groundwater overdraft in portions of the Valley led to the enactment of SGMA in 2014, which established a statewide framework for basin-level groundwater management (SGMA, 2014). This regulatory backdrop underscores the importance of understanding spatial patterns of agricultural consumptive water use across irrigated perennial systems in the region.

In this study, the matched sites are distributed across irrigated portions of the Sacramento Valley, the San Joaquin Valley, the Sacramento–San Joaquin Delta and select interior and coastal-adjacent production areas (Figure 2). All sites are located within actively irrigated perennial

production systems, specifically almond orchards and vineyards. These crops represent dominant long-lived perennial systems in California and are characterized by sustained transpiration during the dry summer season, with water demand governed by atmospheric conditions, canopy development, and irrigation scheduling (Allen et al., 1998; Fereres & Soriano, 2007).

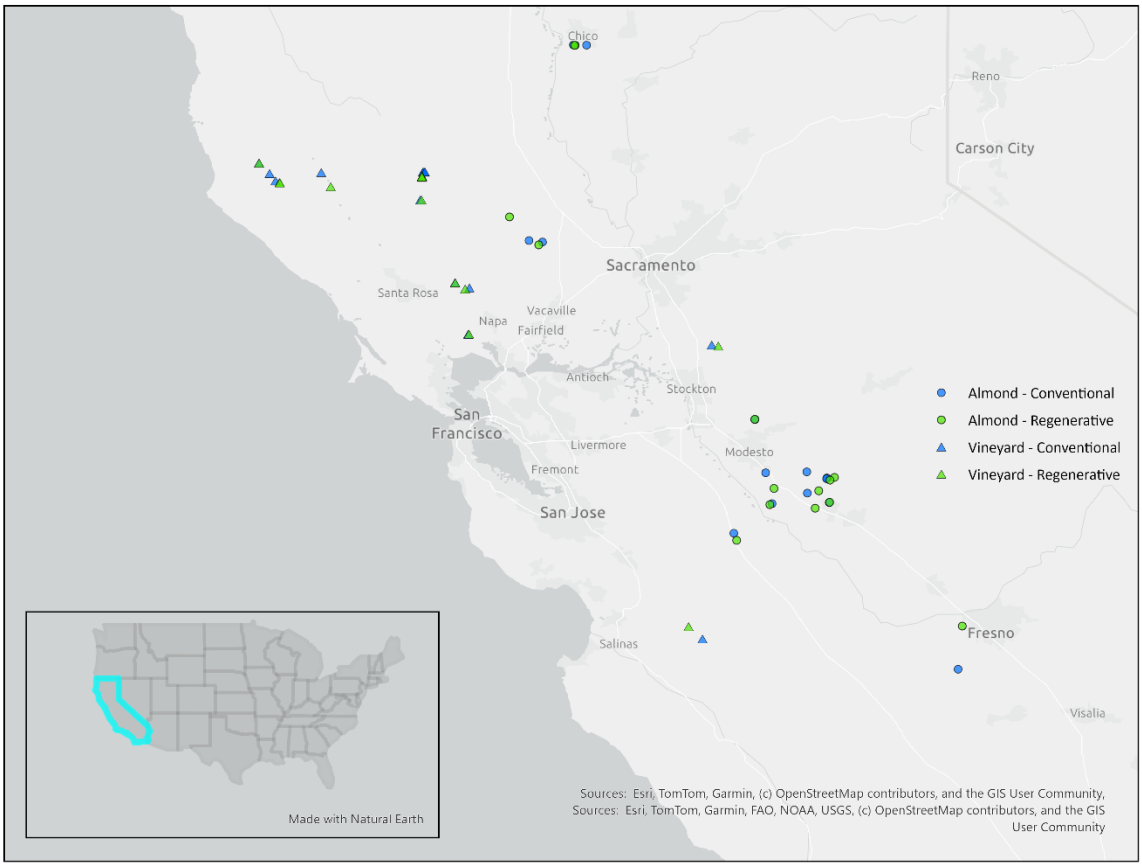


Figure 2: Geographic distribution of matched regenerative and conventional field sites across California. Each point represents an individual field included in the paired comparison design across almond and vineyard systems.

2.3.2 Paired Design and Sample Definition

I employ a matched regenerative–conventional field comparison design within irrigated perennial systems. Site identification and management classification were enabled through collaboration with a research team that conducted on-site ecological and management assessments across almond orchards and vineyards in California. All fields included in this analysis were visited and evaluated in situ. I determined regenerative status using the scoring framework developed and validated by Fenster et al. (2021), which assigns cropland systems a regenerative score on a 1–7 scale based on stacking of regenerative practices. Following this framework, fields with scores above 4 were classified as regenerative, while fields scoring 4 or below were classified as conventional. Crop type was restricted to almond orchards and wine grape vineyards, as these were

the perennial systems for which field-based regenerative scoring and management confirmation were available.

I conducted field pairing using coordinate-based geography and physiographic similarity to approximate shared local hydrologic context. While regenerative–conventional pairs had been identified during field research, final pairing for this analysis was performed using nearest-neighbor logic constrained by geographic proximity and physiographic continuity. The majority of matched pairs were located within approximately two kilometers of one another, several pairs were within eight kilometers, and three pairs were separated by approximately twenty-four kilometers across relatively flat terrain. This approach ensured that paired fields shared broadly similar topographic and hydrologic conditions within the Central Valley landscape.

Lastly, I determined the temporal structure of the dataset by the first year in which field-based management information was available for each site. Because management records were not available for all sites across the full study period, two temporal observation windows were constructed for each crop. This approach reflects a deliberate tradeoff between statistical power and temporal depth. Shorter observation windows increase the number of matched field pairs available for analysis, thereby improving statistical power, whereas longer observation windows preserve extended interannual coverage that allows evapotranspiration patterns to be evaluated across multiple climatic conditions and irrigation seasons. However, these longer windows include fewer pairs because fewer sites have management records extending across the full-time span.

Applying this design, I constructed two analytical groupings for each crop, differing in sample size and temporal coverage. For almond sites, the longer observation window (2019–2025) includes eight matched pairs with extended temporal coverage, while the shorter window (2023–2025) expands the sample to fourteen pairs by incorporating additional sites with more recent management records. For vineyard sites, the longer window (2022–2025) includes seven matched pairs, whereas the shorter window (2024–2025) expands the sample to fourteen pairs, again incorporating the original pairs within a larger but shorter-duration dataset.

2.3.3 Statistical Analysis

I conducted all statistical comparisons within a paired framework. For each matched pair *i*, monthly evapotranspiration (ET) was available as depth estimates (inches) for a conventional field $C_{i,t}$ and its regenerative counterpart $R_{i,t}$ over the specific observation window indexed by month *t*.

The primary comparison was the paired difference in ET between management systems, expressed as:

$$D_{i,t} = C_{i,t} - R_{i,t}$$

where $C_{i,t}$ and $R_{i,t}$ denote monthly ET (inches) for conventional and regenerative fields, respectively. Positive values indicate higher ET in conventional sites relative to regenerative sites.

2.3.3.1 Site-Level Paired Mean Differences

To evaluate whether management systems exhibited systematic differences in consumptive water use, monthly evapotranspiration (ET) observations were first aggregated to the field level. For each field i, I calculated a mean ET value by averaging all available monthly observations

within the relevant study window. This aggregation produces a single mean ET estimate for each field while retaining the full temporal coverage of the dataset. Monthly observations are therefore used only to estimate field-level means, while statistical inference is conducted across matched field pairs.

For conventional fields, the mean ET was calculated as:

$$\bar{C}_i = \frac{1}{T_i}\sum_{t=1}^{T_i} C_{i,t}$$

For regenerative fields, the mean ET was calculated as:

$$\bar{R}_i = \frac{1}{T_i}\sum_{t=1}^{T_i} R_{i,t}$$

where $C_{i,t}$ and $R_{i,t}$ denote monthly ET observations for conventional and regenerative fields respectively, and T_i represents the number of months observed for pair i.

For each matched pair i, I then calculated the paired difference in mean ET:

$$\bar{D}_i = \bar{C}_i - \bar{R}_i$$

Thus, the statistical sample consists of paired field means, with one observation per matched pair.

I performed statistical inference on the set of paired mean differences $\bar{D}_i$, where each observation corresponds to a matched field pair, using a two-sided Wilcoxon signed-rank test comparing conventional and regenerative field means across matched pairs. This non-parametric paired test was selected given modest sample sizes and to avoid reliance on distributional assumptions.

2.3.3.2 Seasonal Structure in Paired Differences

To assess whether differences between management systems were seasonally concentrated, I evaluated paired ET differences by calendar month. Monthly observations were first aggregated within each month-of-year so that comparisons could be made across matched field pairs.

For each pair i and calendar month m, I averaged ET values across all years included in the observation window:

$$\bar{C}_{i,m} = \frac{1}{Y_{i,m}}\sum_{y=1}^{Y_{i,m}} C_{i,m,y}$$

$$\bar{R}_{i,m} = \frac{1}{Y_{i,m}}\sum_{y=1}^{Y_{i,m}} R_{i,m,y}$$

where y indexes year and $Y_{i,m}$ is the number of observed years for month m within pair i.

The month-specific paired difference was then defined as:

$$\bar{D}_{i,m} = \bar{C}_{i,m} - \bar{R}_{i,m}$$

Thus, for each calendar month m, the statistical sample consists of paired differences across matched field pairs.

For each month, I applied a two-sided Wilcoxon signed-rank test across pairs to evaluate whether $\bar{D}_{i,m}$ differed systematically from zero.

Because month-specific tests constitute a multiple-comparison family (12 tests per observation window), p-values were adjusted using both Benjamini–Hochberg false discovery rate (FDR) control and the Holm step-down procedure controlling the family-wise error rate (Benjamini & Hochberg, 1995; Holm, 1979). Month-level significance annotations in figures reflect Benjamini–Hochberg adjusted p-values, with thresholds of $p < 0.05$ (*), < 0.01 (**), and < 0.001 (***). Holm-adjusted values were retained for reporting but were not used for figure annotation.

2.3.3.3 Avoidance of Pseudo-Replication

Although ET observations are available at a repeated month × year × pair resolution, I did not treat repeated measures within pairs as independent sampling units for inference. I conducted site-level tests on pair-level means aggregated across months, and month-of-year seasonality tests were conducted on within-pair month-of-year means aggregated across years.

Raw month × year paired differences $D_{i,t}$ were used for descriptive visualization of dispersion and seasonal variability but were not used as independent inputs to hypothesis tests. This approach preserves the matched pair as the inferential unit and avoids inflation of statistical significance from repeated observations within the same pair.

All analyses were conducted in R (R Core Team, 2024).

2.3.4 OpenET and Unit of Analysis

Monthly evapotranspiration (ET) data were obtained from the OpenET ensemble model. OpenET integrates six satellite-based ET models and processes Landsat imagery at a spatial resolution of 30 × 30 m using Google Earth Engine infrastructure (Gorelick et al., 2017; Melton et al., 2022). The ensemble approach combines model outputs to produce a single ET estimate for each pixel and time step. Independent validation against eddy covariance flux tower measurements across multiple cropland sites indicates strong agreement between OpenET ensemble estimates and ground-based observations, with average R^2 values of 0.96 for monthly ET (Melton et al., 2022). For this study, monthly ensemble ET values were obtained directly from the OpenET platform.

I obtained field-level ET values using OpenET's predefined agricultural field boundaries polygon-based extraction tools. When unavailable, I delineated custom polygons to correspond to individual fields. OpenET internally aggregates 30 m pixel-level ET values within each polygon to generate a single field-level mean ET value for each month. No additional raster processing or post-extraction spatial averaging was conducted outside the OpenET platform. ET values were obtained in inches and retained in depth units throughout the analysis.

2.4 Results

Paired comparisons of evapotranspiration (ET) are presented between conventional and regenerative management systems across matched almond and vineyard sites. ET is evaluated as consumptive water use. Results are reported across multiple analytical scales, beginning with site-level mean differences and extending to monthly trajectories, seasonal paired tests, and distributional assessments within and across matched pairs. For each crop, analyses are shown under two matched-sample definitions: a longer time window with fewer pairs and a shorter, more recent window with expanded site coverage.

To begin, paired site-level mean ET differences (C − R) were estimated across the available time windows for each crop system. For almond sites (2019–2025; n = 8 pairs), paired mean differences were centered slightly above zero (median paired difference = 0.13 in; mean = 0.18 in; Fig. 3A), with both positive and negative values observed across pairs. Positive values indicate higher ET in conventional sites relative to regenerative sites. No statistically significant difference was detected (p = 0.234). For vineyard sites (2022–2025; n = 7 pairs), paired mean differences were similarly centered near zero (median paired difference = 0.08 in; mean = 0.04 in; Fig. 3B), and no statistically significant difference was found (p = 0.80).

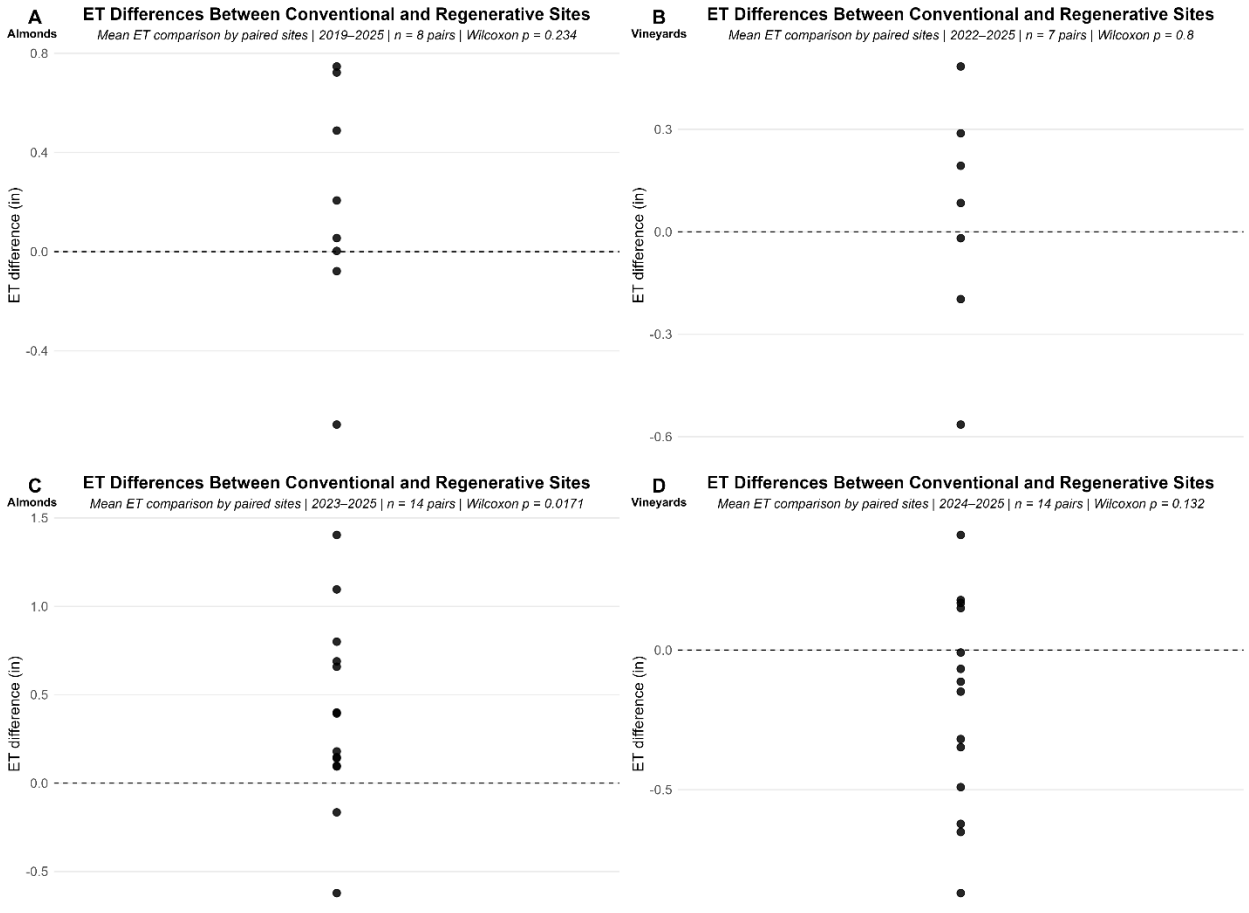


Figure 3: Distribution of paired-site differences in annual mean evapotranspiration (ET) between conventional and regenerative systems. Each point represents the annual mean ET difference (conventional − regenerative) for a matched site pair. The dashed horizontal line indicates no difference between

management systems. Observation windows differ across panels: longer-window smaller samples (A–B) and shorter-window larger samples (C–D). Median and mean paired differences are reported in the main text. Reported p-values correspond to Wilcoxon signed-rank tests evaluating whether paired ET differences differ from zero.

When the matched samples were expanded to include more paired sites over shorter and more recent time windows, distributional patterns shifted. For almond sites (2023–2025; n = 14 pairs), paired mean differences were predominantly positive (median paired difference = 0.29 in; mean = 0.38 in; Fig. 3C), and a statistically significant difference was observed ($p = 0.0171$), with conventional sites exhibiting higher mean ET than regenerative sites. For vineyard sites (2024–2025; n = 14 pairs), paired mean differences remained near zero but slightly negative (median paired difference = −0.13 in; mean = −0.19 in; Fig. 3D), and no statistically significant difference was found ($p = 0.132$). Statistically significant ET differences were therefore detected only in almond sites under the larger matched design, where results showed greater consumptive water use in conventional almond systems relative to regenerative systems. Because the larger matched samples also correspond to shorter and more recent time windows, differences between designs reflect both increased statistical power and potential period-specific dynamics.

To contextualize site-level differences, monthly mean ET trajectories were examined across study periods for each matched sample. As expected for perennial crops with winter dormancy, ET followed a pronounced seasonal cycle in both crop systems. For the 2019–2025 almond sample (n = 8 pairs), monthly mean ET remained near winter lows of approximately 1 inch, increased through spring, peaked above 6 inches in summer, and declined toward late fall (Fig. 4A). Conventional and regenerative trajectories closely tracked one another, with modest separation during peak months. A similar seasonal pattern was observed for the 2023–2025 almond sample (n = 14 pairs), with ET rising sharply in spring, peaking in mid-summer, and declining thereafter (Fig. 4C). In this larger matched sample, separation during peak months was more pronounced, with conventional ET exceeding regenerative ET throughout much of the high-demand period.

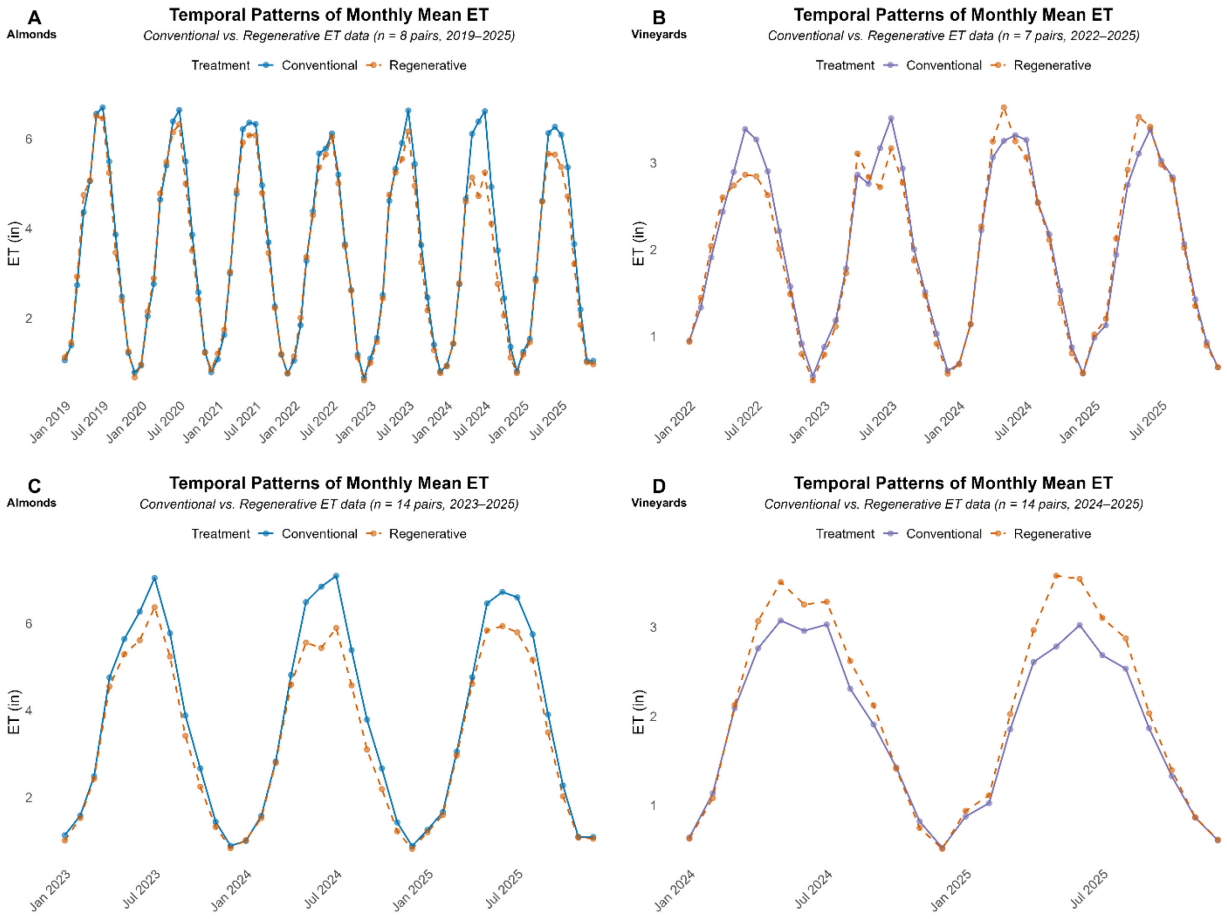


Figure 4: Temporal patterns of monthly mean evapotranspiration (ET) in conventional and regenerative systems across matched site pairs. Lines represent the average monthly ET across paired sites under each management system. Observation windows differ across panels: longer-window smaller samples (A–B) and shorter-window larger samples (C–D).

Vineyard sites exhibited the same cyclical structure but with lower overall ET magnitudes. For 2022–2025 (n = 7 pairs), monthly mean ET ranged from winter lows near 0.6 inches to summer peaks near 3.5 inches (Fig. 4B). Conventional and regenerative trajectories overlapped across most months. The 2024–2025 vineyard sample (n = 14 pairs) displayed the same seasonal progression (Fig. 4D). In this larger sample, regenerative ET slightly exceeded conventional ET during the summer months, although trajectories converged during transitional months.

Across matched samples, ET exhibited consistent seasonal dynamics, with peak consumptive demand occurring during summer and minimal divergence outside of peak periods. Differences between management systems were visually concentrated during mid-summer under the larger matched designs.

To assess whether the observed seasonal pattern was statistically significant, monthly paired ET differences (C − R) were tested between management systems (Fig. 5). For longer time windows with fewer paired sites, monthly differences fluctuated around zero throughout the year. In almond sites (2019–2025; n = 8 pairs), monthly median differences were predominantly positive during late spring and summer, but variability was substantial and no month remained statistically significant after multiple-testing correction (Fig. 5A). Vineyard sites (2022–2025; n = 7 pairs)

exhibited alternating median signs across months, with increased variability during peak periods, and no statistically significant differences were detected after correction (Fig. 5B).

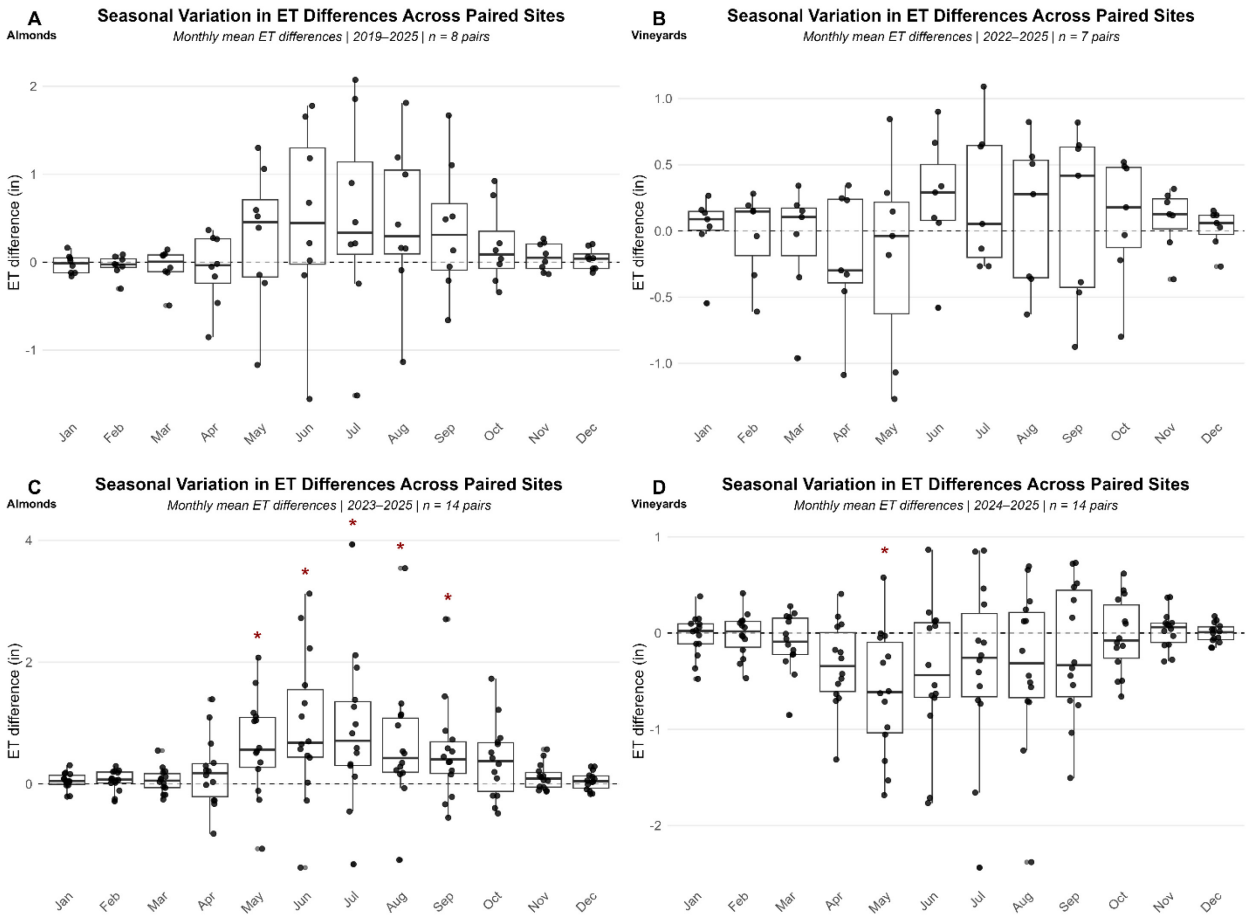


*Figure 5: Seasonal distribution of paired-site differences in monthly mean evapotranspiration (ET) between conventional and regenerative systems. Boxplots show the distribution of ET differences (conventional − regenerative) across matched site pairs for each month. The dashed horizontal line indicates no difference between management systems. Observation windows differ across panels: longer-window smaller samples (A–B) and shorter-window larger samples (C–D). Almond systems are shown in panels A and C, and vineyard systems in panels B and D. Asterisks denote months with statistically significant paired differences based on Benjamini–Hochberg–adjusted p-values (p < 0.05, *p < 0.01, **p < 0.001).*

When larger matched samples were analyzed over shorter windows, seasonal structure became more pronounced (Fig. 5C–D). In almond sites (2023–2025; n = 14 pairs), paired differences were predominantly positive from late spring through early fall, and several mid-season months remained statistically significant after correction (Fig. 5C). These results indicate that the site-level difference in almond systems was driven primarily by divergence during peak summer months rather than uniform separation throughout the year. In vineyard sites (2024–2025; n = 14 pairs), monthly medians were slightly negative overall, with a statistically significant difference detected in May. In other months, differences remained near zero (Fig. 5D). These seasonal results indicate only limited and temporally isolated divergence, consistent with the absence of a statistically significant site-level difference in vineyard systems.

To assess how consistently the observed differences were expressed within matched systems, site-level ET distributions were examined for each pair (Fig. 6). In almond sites, both management systems exhibited considerable within-site variability across months, with interquartile ranges widening during peak growing periods. Under the 2019–2025 sample (n = 8 pairs), several conventional sites showed higher upper-range values relative to regenerative counterparts, although distributions frequently overlapped (Fig. 6A). Under the larger 2023–2025 sample (n = 14 pairs), the positive central tendency remained evident, consistent with the statistically significant site-level and seasonal differences. Although many conventional sites displayed higher medians, regenerative distributions frequently overlapped in range, indicating that divergence was present but not uniformly expressed across all pairs (Fig. 6C).

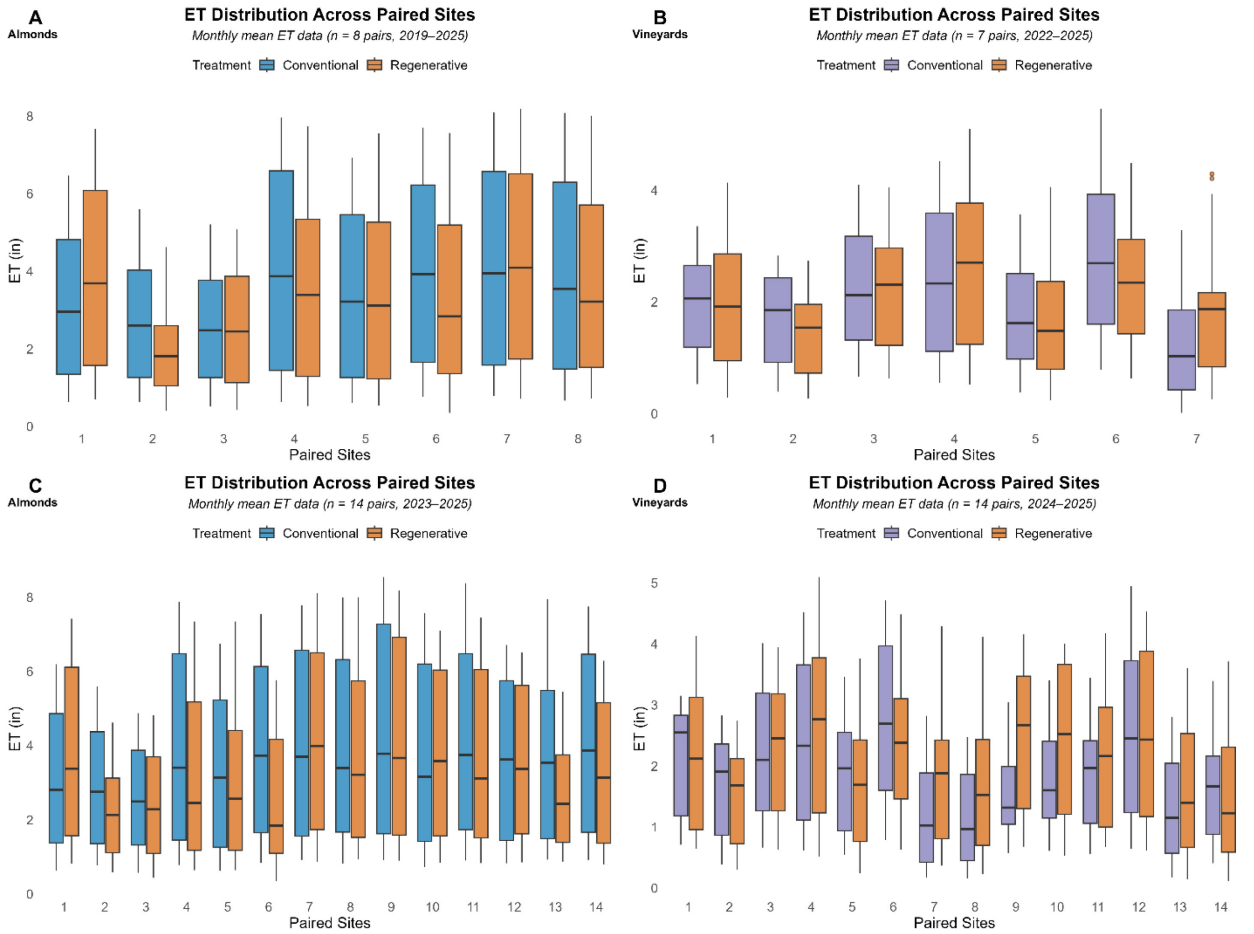


Figure 6: Distribution of monthly evapotranspiration (ET) across matched conventional and regenerative site pairs. Boxplots show the distribution of monthly ET values observed within each site over the study period, illustrating heterogeneity in ET levels across the paired-site sample. Observation windows differ across panels: longer-window smaller samples (A–B) and shorter-window larger samples (C–D).

Vineyard systems showed similar patterns. Across both sample definitions (2022–2025; n = 7 pairs and 2024–2025; n = 14 pairs), ET distributions within paired sites largely overlapped (Fig. 6B/D). In several vineyard pairs, median differences were small relative to within-system variability. Across crops and matched samples, patterns of ET divergence were heterogeneous across paired sites rather than uniformly expressed across all matches.

Lastly, to examine the underlying dispersion and consistency of paired differences across observations, the full distribution of raw month × year × pair ET differences was evaluated (Fig. 7). In almond sites, dispersion widened during late spring and summer, with observations spanning both positive and negative values even in months where medians were above zero (Fig. 7A/C). Under the larger matched sample, mid-season months exhibited a clear positive shift in central tendency, although overlap remained and extreme values occurred in both directions. Outside peak months, differences clustered near zero.

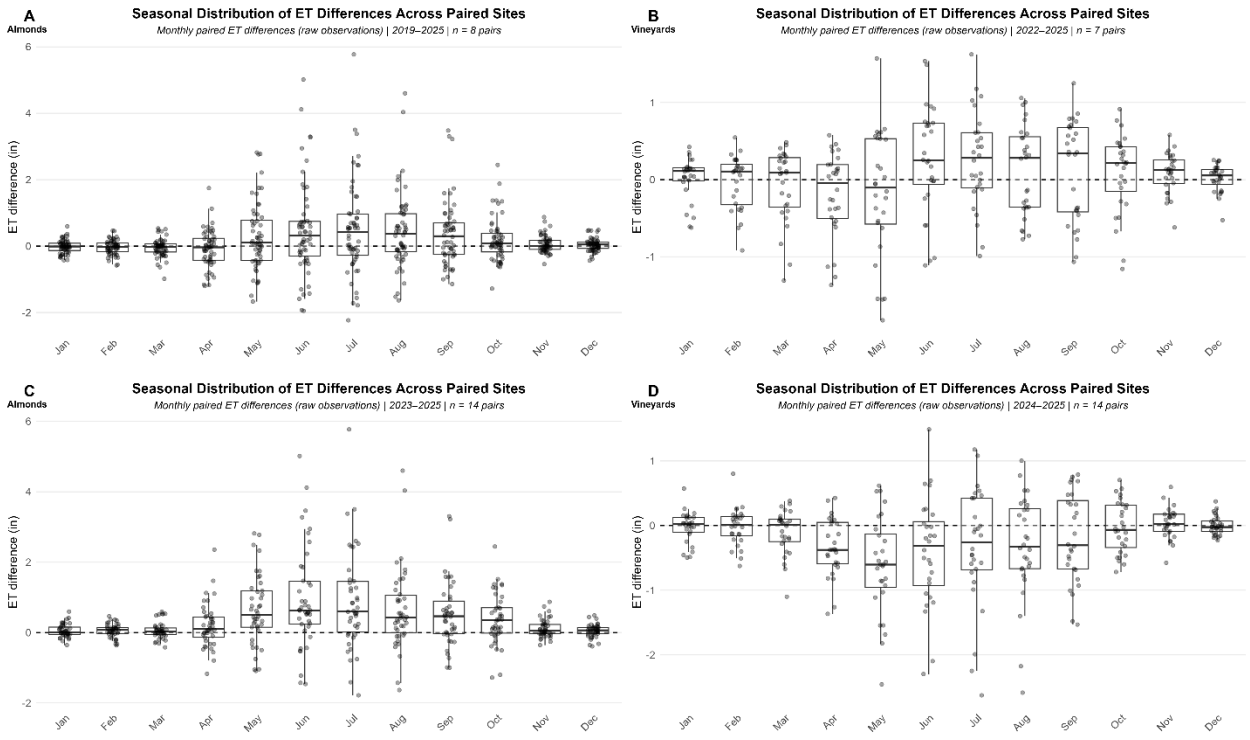


Figure 7: Monthly distribution of paired-site differences in evapotranspiration (ET) between conventional and regenerative systems. Boxplots show the distribution of ET differences (conventional − regenerative) across matched site pairs for each month, illustrating how the magnitude and variability of treatment differences shift throughout the year. The dashed horizontal line indicates no difference between management systems. Observation windows differ across panels: longer-window smaller samples (A–B) and shorter-window larger samples (C–D).

In vineyard systems, raw paired differences likewise displayed substantial within-month variability (Fig. 7B/D). Spring and summer months showed broader spreads, including observations diverging in opposite directions within the same month. Even where median differences suggested a seasonal tendency, individual pair-level observations frequently crossed zero, indicating that aggregate patterns did not reflect uniform directional change across all sites or years.

Across crops and matched samples, seasonal patterns therefore represent aggregate tendencies rather than consistent directional shifts across all paired observations. In the larger almond sample, however, a positive central tendency persisted, consistent with statistically significant site-level and seasonal results and indicating greater consumptive water use in conventional almond systems during the growing season.

2.5 Discussion

I evaluated whether regenerative management is associated with differences in consumptive water use relative to conventional systems in irrigated perennial crops. Using matched regenerative–conventional field pairs and satellite-derived evapotranspiration (ET) estimates, I examined site-level means, seasonal structure, and distributional variability across almonds and vineyards. Statistically detectable differences emerged only in almond systems under the larger matched design (2023–2025; n = 14 pairs), where conventional orchards exhibited higher ET than regenerative counterparts. This divergence was concentrated during peak summer months rather than uniformly expressed throughout the year. Vineyard systems showed no consistent site-level difference across either sample definition, while seasonal tests revealed occasional month-level deviations in both directions that did not persist across months or observation windows. Across crops, dispersion within matched pairs remained substantial, indicating that statistically detectable differences reflected shifts in central tendency rather than uniform directional change across all sites.

For almonds, my findings suggest that regenerative management may be associated with moderated peak-season consumptive demand under certain conditions. In the expanded matched sample, positive paired differences (C − R) were concentrated from late spring through early fall, indicating higher ET in conventional orchards during periods of maximum atmospheric demand. This pattern is consistent with the field-scale observations of Flynn et al. (2025), who reported similar winter ET and comparable or slightly lower growing-season ET in regenerative almond orchards despite enhanced infiltration and soil moisture retention. Together, these findings indicate that regenerative soil improvements do not increase consumptive water use and may, in some systems, coincide with reduced peak-season atmospheric flux.

Importantly, regenerative agriculture is explicitly oriented toward increasing biodiversity, soil organic matter, and biological activity (Adamczewska-Sowińska et al., 2022; Fenster et al., 2021; Xu et al., 2022). Empirical studies of cover cropping systems have likewise documented increased seasonal water use relative to bare soil during active growth periods (Blanco-Canqui et al., 2015; Mitchell et al., 2017). However, for perennial systems, my results do not support that concern. In vineyard systems, no systematic increase in ET was observed under regenerative management. In almond systems, regenerative orchards did not exhibit higher winter ET despite the likely presence of cover crops in regenerative fields during dormant periods. My findings suggest that regenerative practices aimed at enhancing soil and ecological functioning can be implemented without imposing additional consumptive water demand relative to conventional systems. Where differences were detected, they favored lower peak-season ET in regenerative almond systems.

Hydrologically, this pattern is consistent with the understanding that evapotranspiration reflects the integrated interaction of soil moisture availability, plant physiology, and atmospheric forcing (Allen et al., 1998; Wong et al., 2021). While improvements in soil structure and water holding capacity increase the capacity of soils to retain moisture, they do not mechanically determine total atmospheric water loss. As Lankford and Orr (2022) emphasized, consumptive use depends on the extent to which crops approach their potential evapotranspiration under prevailing environmental conditions. My findings therefore clarify an important point: regenerative agriculture's soil and biodiversity gains do not inherently require higher consumptive flux. Rather than assuming that ecological intensification must entail greater water demand, the evidence

suggests that regenerative systems can maintain or even modestly moderate ET under irrigated perennial conditions.

My results indicate that this distinction carries practical implications under California's Sustainable Groundwater Management Act (SGMA, 2014). Because evapotranspiration represents the dominant pathway through which irrigation water leaves the hydrologic basin, ET serves as a policy-relevant measure of consumptive water use. The results presented here indicate that regenerative management does not impose additional basin-level atmospheric water loss relative to conventional systems and, for almonds, may reduce peak-season demand. In this sense, regenerative agriculture's soil health and biodiversity improvement objectives appear compatible with groundwater sustainability goals. Rather than requiring trade-offs between ecological restoration and water accounting, regenerative systems can be implemented without increasing consumptive water use, thereby aligning environmental co-benefits with SGMA-relevant water management constraints.

The paired design employed here isolates management contrasts while holding regional climatic conditions broadly constant within each comparison, and inferential tests were conducted at the matched-pair level to avoid pseudo-replication. Monthly ET estimates were derived from the OpenET ensemble, which has demonstrated strong agreement with eddy covariance measurements in irrigated cropland (Melton et al., 2022), providing confidence in the reliability of the consumptive water estimates used in this analysis. At the same time, several limitations shape interpretation. Satellite-derived ET does not partition evaporation and transpiration, constraining direct identification of the physiological mechanisms underlying observed differences. The larger matched samples correspond to shorter and more recent time windows, making it difficult to fully disentangle increased statistical power from potential period-specific climatic dynamics. ET depth reflects atmospheric water loss but does not capture irrigation volumes, timing, or return flows. In addition, regenerative classification was based on a composite scoring framework (Fenster et al., 2021), precluding isolation of individual management practices responsible for observed patterns. My results should therefore be interpreted as management-associated differences in consumptive water use rather than causal estimates of specific practice effects.

Future research can build on these findings by extending longitudinal coverage across broader climatic cycles and integrating ET analysis with field-level irrigation records to clarify how applied water relates to atmospheric demand under regenerative management. Direct field instrumentation capable of partitioning evaporation and transpiration would further strengthen mechanistic understanding of how soil structural improvements interact with crop physiology. Crop-specific physiological studies may help explain why moderated peak-season ET emerged in almond systems but not in vineyards. Expanding matched designs across additional perennial systems would also clarify the extent to which the patterns observed here generalize across irrigated agroecosystems.

2.6 Conclusion

In this study, I directly evaluated whether regenerative management alters consumptive water use in irrigated perennial systems by comparing matched regenerative and conventional orchards and vineyards using field-scale evapotranspiration estimates. The results indicate that regenerative agriculture does not require increased atmospheric water loss relative to conventional management. In almond systems, regenerative orchards were associated with moderated peak-season evapotranspiration under an expanded matched design, while vineyard systems exhibited

no systematic increase in consumptive use. These findings suggest that regenerative management can operate within comparable hydrological bounds while pursuing ecological objectives.

Importantly, regenerative agriculture is often characterized by increased biodiversity, soil organic matter, and biological activity. Such ecological intensification could plausibly be expected to increase water demand if greater biomass translated directly into higher transpiration. However, the evidence presented here does not support that concern. Across crops and matched samples, regenerative systems did not impose additional consumptive flux, and in almonds, peak-season atmospheric water loss was lower under regenerative management. These results indicate that soil restoration and biodiversity enhancement need not come at the cost of increased water demand in irrigated perennial systems.

In water-constrained regions such as California's Central Valley, where groundwater sustainability depends on accurate accounting of consumptive use, this compatibility is consequential. Regenerative agriculture appears capable of advancing soil health and ecological resilience without increasing basin-level atmospheric water loss. By directly measuring evapotranspiration rather than inferring outcomes from soil indicators alone, I contributed empirical clarity to ongoing debates regarding the water implications of regenerative management. In sum, my findings suggest that regenerative agriculture can align ecological regeneration with hydrological responsibility, reinforcing its potential role in resilient and groundwater-compatible agroecosystems.

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CHAPTER 3: "A Field in Motion, Not in Alignment": Expansion without Stabilization in Sustainability Transitions

Abstract

Regenerative agriculture (RA) has gained increasing attention as governments, corporations, and financial actors seek pathways toward more resilient agri-food systems. Still, despite its rapid expansion across policy, market, and scientific domains, RA remains characterized by contested meanings, fragmented governance arrangements, and limited institutional consolidation. Existing sustainability transitions research commonly associates diffusion with increasing alignment and stabilization across socio-technical systems. In this paper, I challenge this assumption by examining how emerging sustainability fields may expand without achieving institutional stabilization. Drawing on 48 semi-structured interviews with actors across farming, certification, finance, policy, academia, and supply chains, as well as participant observation at regenerative agriculture events, I analyze how regenerative agriculture develops under conditions of converging landscape pressures and persistent institutional incompleteness. Using an abductive and mechanism-based qualitative approach, I identify a distinct field-level configuration conceptualized as expansion without stabilization. Findings show that converging pressures linked to climate concerns, supply chain risk, ESG commitments, carbon markets, and economic de-risking generate multiple and heterogeneous pathways of entry into regenerative agriculture, enabling rapid diffusion without requiring prior alignment around shared standards or definitions. At the same time, stabilization is systematically inhibited by institutional frictions across governance, market, and knowledge domains. Certification systems, fragmented demand, policy misalignment, and contested interpretations reproduce ambiguity and prevent convergence around coherent evaluative frameworks. Despite these conditions, coordination does not collapse. Instead, it is sustained through adaptive and provisional mechanisms, including outcome-based framing, intermediary translation, flexible certification approaches, and temporary incentive structures. By identifying expansion without stabilization as a distinct transition configuration, this study contributes to sustainability transitions research by reconceptualizing the relationship between diffusion, stabilization, and coordination under conditions of accelerating and interacting pressures.

3.1 Introduction

Sustainability transitions research is increasingly confronted with the challenge of understanding not only whether systemic change occurs, but how it unfolds under conditions of accelerating and interacting pressures. Recent scholarship emphasizes that transitions are shaped by the convergence of landscape pressures, including climate urgency, industrial restructuring, policy intervention, and market reconfiguration, that operate simultaneously (Andersen et al., 2026; Markard et al., 2020). The growing focus on policy mixes further shows how combinations of regulatory, infrastructural, and market conditions produce divergent trajectories, from rapid reconfiguration to stalled or uneven change (Juntunen & Shakeel, 2026). Taken together, these developments reframe transitions as processes conditioned by converging pressures, raising

questions about how such pressures shape not only the pace of change, but also the coordination and institutional development of emerging socio-technical fields.

Foundational contributions conceptualize transitions as multi-level processes in which landscape pressures destabilize regimes and create opportunities for emerging niches (Geels, 2002; Geels et al., 2023; Geels & Schot, 2007). As transitions progress, diffusion is typically associated with increasing institutional coordination, including the alignment of rules, infrastructures, and actor expectations that support stabilization (Köhler et al., 2019; Markard et al., 2012), even as these processes remain contested and uneven (Turnheim et al., 2020). This raises a central question: how do accelerating and interacting landscape pressures reshape the relationship between diffusion and institutional stabilization in socio-technical innovations?

Recent contributions call for closer integration between innovation diffusion, structural transformation, and governance dynamics, emphasizing that institutional adaptation often lags behind or misaligns with the pace and complexity of ongoing change (Geels et al., 2023; Rosenbloom, 2025; Weckowska et al., 2025). This gap is especially salient at the level of field stabilization, where meanings, standards, and governing arrangements may remain unsettled even as alternatives expand (Juntunen & Shakeel, 2026; Weckowska et al., 2025). Examining these dynamics in empirical settings provides a critical opportunity to understand how emerging sustainability fields are coordinated under conditions of accelerating change.

Regenerative agriculture provides a strategic empirical setting for examining these dynamics. Broadly defined as an approach to farming that seeks to restore soil health, enhance biodiversity, and improve ecosystem functioning while maintaining productive capacity, it has gained increasing attention across scientific, policy, and industry domains (Lal, 2020; Newton et al., 2020; Schreefel et al., 2020; Schulte et al., 2022; Wilson et al., 2025). Still, it remains a heterogeneous and contested concept, encompassing diverse practices, metrics, and interpretations that vary across actors and contexts (Newton et al., 2020; Wilson et al., 2025). Agri-food transitions research further highlights the complexity of coordinating sustainability-oriented change in this domain, where production systems are embedded in ecological processes, global supply chains, and evolving governance arrangements (El Bilali, 2019; Schiller et al., 2023). Positioned at the intersection of climate mitigation, biodiversity conservation, corporate sourcing, financial innovation, and policy experimentation, regenerative agriculture offers a useful case for examining how emerging sustainability fields expand and coordinate under converging pressures.

I examine how converging landscape-level pressures shape the expansion and coordination of regenerative agriculture as an emerging sustainability field. Drawing on qualitative analysis, I analyze how accelerating sustainability demands interact with evolving institutional conditions. I focus on how regenerative agriculture is interpreted, organized, and governed under conditions of partial, shifting, and at times misaligned institutional support. As such, in this paper I contribute to sustainability transitions research by challenging the assumption that diffusion is contingent on prior stabilization and institutional alignment in emerging sustainability fields. First, I show that converging landscape pressures do not only destabilize existing regimes but actively structure multiple and heterogeneous pathways through which alternative fields expand, enabling diffusion without prior alignment. Second, I demonstrate that field stabilization, particularly the consolidation of meanings, standards, and evaluative criteria, does not necessarily follow expansion and may be actively inhibited by existing institutional arrangements, which generate persistent fragmentation rather than convergence. Third, I show that under these conditions, coordination is not contingent on institutional consolidation but is instead sustained through adaptive and provisional mechanisms that enable alignment without standardization.

3.2 Transitions as Processes of Alignment and Stabilization

Sustainability transitions are commonly conceptualized as long-term processes of systemic reconfiguration in which novel socio-technical configurations emerge, gain momentum, and progressively transform established systems (Geels, 2002, 2010; Geels et al., 2023). The Multi-Level Perspective (MLP) provides a foundational framework for understanding these dynamics, emphasizing interactions between niche innovations, socio-technical regimes, and broader landscape pressures (Geels, 2002; Geels et al., 2023). Within this perspective, transitions unfold as niche innovations develop internal coherence, align with external conditions, and gradually challenge and reconfigure dominant regimes.

A central implication of this framework is that the broader diffusion of innovations is closely tied to processes of alignment and structuration unfolding across distinct transition phases (Geels, 2002; Geels et al., 2023). In early phases, niche innovations are characterized by experimentation, variation, and high uncertainty, as actors explore alternative configurations. As transitions progress, successful niche innovations develop momentum through the increasing alignment of expectations, actor networks, institutional support, and socio-technical configurations, enabling broader coordination and more stable patterns of diffusion (Geels et al., 2023; Geels & Schot, 2007). This process of structuration provides the basis for diffusion, in which innovations expand beyond protected niches and engage more directly with regime-level dynamics.

In this sense, diffusion is understood not merely as an increase in adoption, but as a process of embedding within broader socio-technical systems, through which emerging configurations scale, coordinate, and reproduce across contexts. This involves the gradual alignment of technologies, infrastructures, user practices, market structures, and policy frameworks, which support the coordination and reproduction of the emerging configuration (Köhler et al., 2019; Markard et al., 2012). Thus, diffusion reflects increasing system coherence, as previously fragmented elements become more tightly integrated and mutually reinforcing (Markard, 2018).

Recent work on transition acceleration further emphasizes that periods of rapid expansion are typically associated with the amplification of these alignment processes (Juntunen & Shakeel, 2026; Sovacool & Geels, 2016). As innovations gain traction, reinforcing feedbacks, such as performance improvements, growing actor networks and intermediation, and supportive institutional adjustments, enable faster diffusion and broader system impact (Kivimaa et al., 2019; Markard et al., 2020; Sovacool & Geels, 2016). While such processes are not strictly linear and may involve ongoing contestation and uneven development, acceleration is generally understood to build upon, and intensify, the structuration of emerging configurations rather than bypass it.

From this perspective, stabilization emerges as the outcome of cumulative alignment across system elements. It involves the consolidation of shared meanings, governance arrangements, and evaluative criteria that enable consistent coordination across actors and contexts (Fuenfschilling, 2019; Rogge & Reichardt, 2016). Although transitions remain contested and dynamic, the dominant expectation within sustainability transitions research is that diffusion and stabilization are closely intertwined processes, in which expanding participation is accompanied by increasing institutional coherence and system integration (Sovacool & Geels, 2016; Turnheim et al., 2020).

3.3 Acceleration, Complexity, and Institutional Misalignment in Transitions

Despite the expectation that diffusion is accompanied by increasing alignment and stabilization, recent work shows that contemporary sustainability transitions often unfold under conditions that challenge this trajectory (Markard et al., 2020; Sovacool & Geels, 2016). Markard et al. (2020) show that accelerating transitions involve the expansion of innovations across multiple systems and domains, driven by increasing pressures to address sustainability challenges and by the need to align innovations with broader system changes. Complementing this, Sovacool and Geels (2016) show that energy transitions involved the co-evolution of diverse technological, institutional, and market elements across multiple dimensions, resulting in heterogeneous and uneven transformation processes rather than a single, unified trajectory. Taken together, diffusion may proceed through the expansion of heterogeneous and only partially aligned configurations, rather than through the progressive consolidation of stabilized and unified system arrangements.

These diffusion dynamics are further shaped by the configurational nature of transition environments. Rather than operating within unified institutional frameworks, transitions are embedded in complex policy mixes that combine multiple instruments, actors, and objectives across different scales (Kern & Rogge, 2018; Rogge & Reichardt, 2016). Empirical analyses show that such policy mixes often contain both complementary and conflicting elements, generating uneven incentives and fragmented support structures for emerging innovations (Howlett & Rayner, 2007; Kern & Howlett, 2009). As highlighted by Juntunen and Shakeel (2026), sustainability transition outcomes depend not on the effectiveness of individual policies in isolation, but on how different institutional and infrastructural components interact, often producing outcomes that are context-dependent, contingent, and only partially coordinated. Under these conditions, alignment across system elements becomes a situated and uncertain achievement rather than an inherent feature of diffusion processes.

At the same time, processes of institutionalization themselves are increasingly recognized as contested and uneven. Rather than converging toward shared meanings and stable governance arrangements, transitions frequently involve ongoing struggles over problem definitions, solution pathways, and evaluative criteria (Fuenfschilling, 2019; Lempiälä et al., 2019; Turnheim et al., 2020). For instance, Fuenfschilling (2019) shows how competing institutional logics shaped the framing and evaluation of emerging innovations, leading actors to advance divergent interpretations of what constitutes legitimate practices and desirable outcomes. As a result, institutional development may proceed unevenly across domains, generating persistent misalignments between technological change, market formation, regulatory frameworks, and societal expectations.

3.4 Stabilization and Coordination in Emerging Sustainability Fields

These conditions of persistent misalignment raise a fundamental question regarding the relationship between diffusion and stabilization in emerging sustainability fields. While transitions are commonly analyzed at the level of socio-technical systems, these processes are also constituted through the formation and evolution of organizational and institutional fields, in which diverse actors interact, negotiate meanings, and establish the rules that govern participation (Fligstein & McAdam, 2011). From this perspective, stabilization involves more than the alignment of technological and infrastructural elements; it entails the consolidation of shared understandings, evaluative criteria, and governance arrangements that enable coordinated action across heterogeneous actors (Fuenfschilling, 2019).

Within this literature, field stabilization is typically understood as a critical condition for sustained coordination and reproduction, as it enables the alignment of actors, practices, and evaluative frameworks across a given domain (Fligstein & McAdam, 2011; Fuenfschilling, 2019). As emerging fields develop, actors engage in processes of categorization, legitimation, and institutionalization that reduce uncertainty and facilitate broader participation (Durand et al., 2017; Fuenfschilling & Truffer, 2014; Navis & Glynn, 2010). The establishment of shared definitions and standards allows actors to interpret practices consistently, evaluate outcomes, and align expectations, thereby supporting the expansion and consolidation of the field (Fuenfschilling, 2019; Greenwood et al., 2011; Lempiälä et al., 2019). In this sense, stabilization provides an institutional and cognitive infrastructure through which diffusion can be sustained and coordinated over time.

At the same time, recent work suggests that coordination does not necessarily depend on fully stabilized institutional arrangements but may instead be achieved through more flexible and distributed mechanisms, particularly in complex and rapidly evolving contexts (Gaitán-Cremaschi et al., 2024; Kivimaa et al., 2019; Mignon & Bastås, 2025). Intermediary actors, for instance, can facilitate alignment across domains by translating between different knowledge systems, connecting otherwise disconnected actors, and enabling forms of collaboration that do not rely on fully standardized rules or centralized governance (Kivimaa et al., 2019). Similarly, emerging forms of coordination may rely on shared problem framings, provisional evaluation criteria, and project-based or experimental arrangements that allow actors to engage with common objectives without requiring full agreement on underlying definitions or practices (Lempiälä et al., 2019; Mignon & Bastås, 2025). These accounts point to the possibility that coordination can be sustained under conditions of partial and evolving stabilization, where alignment remains incomplete and continuously negotiated.

Despite these advances, I argue that existing research continues to associate the expansion of sustainability fields with processes of increasing stabilization and institutional consolidation, while offering more limited insight into situations where stabilization remains incomplete or persistently contested. This leaves open the question of how emerging sustainability fields expand and are coordinated under conditions where stabilization remains incomplete. In what follows, I examine these dynamics by focusing on the mechanisms through which converging pressures enable heterogeneous participation, inhibit the consolidation of meanings and evaluative criteria, and sustain coordination through adaptive and provisional arrangements rather than stabilized and standardized forms.

3.5 Methods

3.5.1 Research Design and Analytical Approach

This study adopts a qualitative, theory-building research design to investigate how emerging sustainability fields form and are coordinated under conditions of persistent institutional complexity and incomplete alignment. Case-based qualitative research is particularly suited for developing processual explanations of complex phenomena, as it enables close examination of interactions, interpretations, and coordination dynamics as they unfold in practice (Eisenhardt & Graebner, 2007; Siggelkow, 2007). Within sustainability transitions research, such approaches enable examination of how field-level dynamics are constructed and coordinated in practice, rather than inferred from aggregate patterns or system-level models.

Analytically, I follow an abductive approach, involving iterative movement between empirical observations and theoretical concepts (Dubois & Gadde, 2002; Timmermans & Tavory, 2012). Abduction is particularly suited to contexts where existing theories provide only partial explanatory leverage, enabling refinement and extension of theoretical expectations through empirical analysis (Dubois & Gadde, 2002; Timmermans & Tavory, 2012). In this study, abductive analysis involved iterative engagement with sustainability transitions literature and remained open to empirical patterns that do not conform to established assumptions.

Consistent with this approach, the analysis is oriented towards identifying mechanisms that explain how field-level processes unfold, rather than toward describing themes or categorizing actor perspectives. Mechanisms are understood as recurrent, generative patterns that account for how outcomes are produced across contexts (Hedström & Ylikoski, 2010). This mechanism-based orientation supports the development of an analytically explicit account of field dynamics by linking empirically grounded observations to higher-order theoretical constructs.

3.5.2 Empirical Setting: Regenerative Agriculture as an Emerging Sustainability Field

This study is situated in the empirical setting of regenerative agriculture, commonly associated with efforts to restore soil health, enhance biodiversity, and improve ecosystem functioning while maintaining productive capacity (Lal, 2020; Schreefel et al., 2020). However, evidence from academic literature shows that both the practices associated with regenerative agriculture and the criteria used to evaluate them vary substantially across contexts and actors (Newton et al., 2020; Wilson et al., 2025). Rather than treating regenerative agriculture as a fixed or standardized model of production, this study approaches it as an emerging sustainability field in which diverse actors engage with a loosely defined set of practices, principles, and outcomes across multiple domains, including farming, supply chains, finance, policy, and certification.

At the same time, regenerative agriculture has experienced rapid expansion across scientific, policy, and market domains. Corporate commitments have scaled significantly, with major agri-food companies such as General Mills and Nestlé collectively pledging to transition millions of acres to regenerative practices as part of broader net-zero and supply chain sustainability strategies (General Mills, 2025; Nestlé, 2023). Public investment has also increased, most notably through large-scale initiatives such as the USDA's Partnerships for Climate-Smart Commodities program, which allocated over $3 billion to support climate-smart and regenerative agricultural practices across the United States (USDA NRCS, 2025). In parallel, market and financial interest has grown, with reports estimating that regenerative agriculture could represent a multi-billion-dollar market opportunity linked to carbon markets, ecosystem services, and sustainable supply chains (McKinsey & Company, 2021). Academic output has similarly expanded, with a marked increase in publications addressing regenerative agriculture's practices, impacts, and governance over the past decade (Newton et al., 2020). Together, these developments indicate a broad-based acceleration in attention, investment, and engagement around regenerative agriculture across multiple institutional domains.

This combination of rapid expansion, institutional heterogeneity, and ongoing contestation makes regenerative agriculture a suitable empirical setting for examining how emerging sustainability fields develop under conditions of complexity and evolving institutional support. Prior research has shown that sustainability transitions often unfold through the interaction of multiple institutional logics and actor groups within emerging fields, where coordination and meaning remain in flux (Fuenfschilling, 2019; Fuenfschilling & Truffer, 2014). Situating

regenerative agriculture within this perspective provides an empirically relevant setting for examining field formation in sustainability transitions.

3.5.3 Data Collection

The empirical material for this study draws on 48 semi-structured interviews conducted with actors engaged in regenerative agriculture across multiple sectors. Interviewees included growers, consultants, extension agents, funders, agribusiness representatives, certifiers, academics, policy experts, and financial actors (Table 8). Growers constitute the largest group of participants, reflecting their central role in implementing and adapting regenerative practices under site-specific conditions. At the same time, the inclusion of actors from policy, finance, certification, and supply chains allows examination of how field-level dynamics are structured through interacting institutional logics, incentives, and coordination mechanisms.

Table 8: Interviewee distribution by actor category.

Actor category	Role in the field	N
Farmers	On-the-ground implementation of regenerative practices and site-level adaptation	22
Consultants	Advisory support and translation of practices across contexts	5
Extension agencies	Knowledge dissemination and technical assistance	5
Academics	Research, conceptual framing, and evidence generation	3
Food businesses	Supply chain coordination and market interface	3
Funding agencies	Capital provision and program design	3
Certifiers	Standards development and verification systems	2
Finance	Lending, investment, and risk assessment	2
Policy experts	Regulatory design and policy analysis	2
Agronomy businesses	Product commercialization and technical services	1
Total		**48**

I conducted interviews primarily in California, with additional participants from other regions of the United States included to capture variation in how regenerative agriculture is interpreted and organized across different contexts. Participants were recruited through a combination of purposive sampling, targeted outreach to identified stakeholders, and snowball sampling, including referrals from interviewees and contacts established during industry events (Noy, 2008; Patton, 2014). This multi-pronged recruitment strategy enabled coverage of diverse roles, perspectives, and positions within the emerging field.

The interview protocol focused on participants' experiences with regenerative agriculture, including pathways into engagement, perceived opportunities and constraints, institutional and market conditions, and forms of interaction and coordination across actors. While interviews were not designed to elicit standardized accounts of field development, participants frequently described how regenerative agriculture is interpreted, implemented, and debated across contexts. These accounts provided rich empirical material for examining patterns of participation, constraint, and coordination within an emerging field.

In addition to interviews, participant observation was conducted at 17 regenerative agriculture–related events, totaling over 100 hours. These observations included workshops, conferences, and multi-stakeholder convenings, and were used to contextualize interview data by capturing how regenerative agriculture is collectively discussed, framed, and negotiated across actors and domains (Spradley, 2016). Observational data provided insight into how meanings, evaluation criteria, and coordination practices are articulated and contested in situ, complementing interview accounts.

3.5.4 Data Analysis

I followed an abductive approach in data analysis informed by principles of grounded theory (Charmaz, 2014), involving iterative movement between empirical material and theoretical concepts (Timmermans & Tavory, 2012). This approach enabled the development of explanations grounded in participants' accounts and oriented toward broader theoretical constructs. Initial coding remained closely aligned with participants' language and interpretations, generating first-order categories capturing how actors described their engagement with regenerative agriculture and the conditions shaping their participation. These categories were not predefined but emerged through close engagement with the data.

Subsequent analysis involved systematic abstraction from these empirically grounded categories through multiple levels of analytical abstraction, consistent with the hierarchical coding logic outlined by Gioia et al. (2013). First-order codes captured the content of participants' accounts and provided empirical grounding. These were then abstracted into mechanisms, understood as recurrent, generative patterns that explain how field-level processes unfold. Mechanisms were subsequently grouped into higher-order constructs, representing analytically distinct dimensions of field dynamics, which were further integrated into broader theoretical layers capturing the configuration of the field.

Throughout the analysis, I iteratively compared interviews and data sources to support the refinement of categories at each level of abstraction. This hierarchical progression, from first-order codes to mechanisms, from mechanisms to constructs, and from constructs to theoretical layers, provided an analytically transparent basis for linking empirical observations to a multi-level theoretical explanation of field formation.

3.6 Findings: Expansion without stabilization

I show that regenerative agriculture challenges the conventional sequential progression of field formation. In standard transition accounts, processes of alignment and stabilization precede and enable broader diffusion. However, under sustained and converging external pressures, regenerative agriculture expanded rapidly, with participation broadening and field activity intensifying, while stabilization remained incomplete (Figure 8). Rather than stabilization enabling expansion, expansion proceeds independently of, and in tension with, stabilization processes.

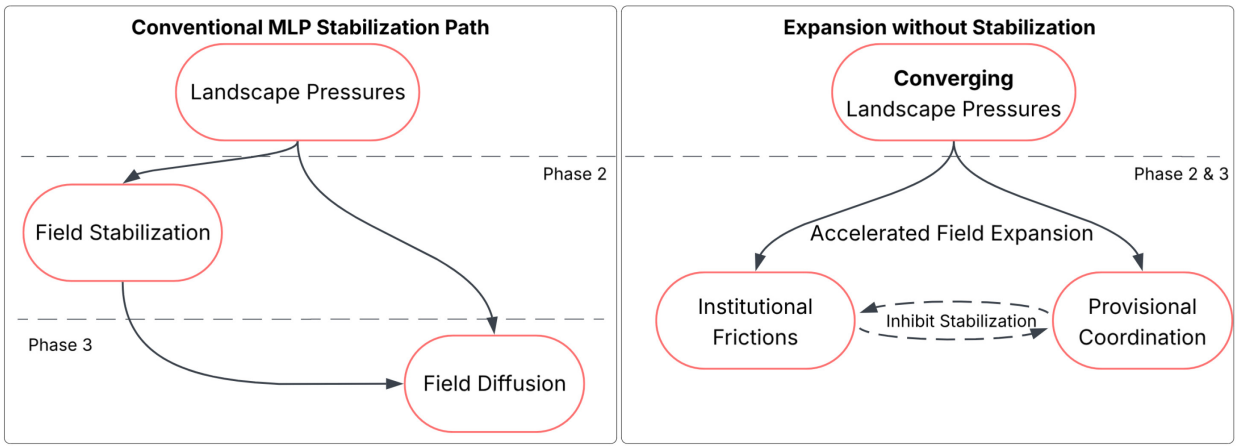


Figure 8: Expansion without stabilization: decoupled field development under converging pressures.

I conceptualize this dynamic as expansion without stabilization. This refers to a field-level process in which diffusion occurs in the absence of stabilized meanings, standards, or institutional arrangements, and where coordination is sustained through adaptive and provisional mechanisms rather than consolidated structures. In this configuration, expansion is decoupled from stabilization, unfolding alongside persistent contestation and institutional incompleteness rather than being contingent upon their resolution.

Empirically, this pattern is observable in the coexistence of broadening participation and ongoing fragmentation in how regenerative agriculture is defined, measured, and governed. At the same time, coordination emerges through flexible and evolving arrangements rather than converging into standardized forms. The sections that follow unpack this configuration by examining how converging pressures accelerate expansion, how institutional frictions inhibit stabilization, and how provisional coordination sustains field activity under conditions of incomplete consolidation.

3.6.1 Landscape Pressures Driving Field Expansion

Field expansion is driven by the convergence of multiple, domain-specific pressures that collectively accelerate participation without requiring prior coordination (Figure 9). Rather than a single dominant driver, expansion emerges from the interaction of economic, financial, corporate, and socio-environmental logics that incrementally lower distinct barriers to entry (Table 9). Economic de-risking makes regenerative practices materially viable by reducing exposure to input costs and production uncertainty, while financial mechanisms such as carbon markets introduce new entry points that enable participation despite weak standardization. At the same time, corporate actors are mobilized through the alignment of supply chain risk management and ESG-driven legitimacy pressures, integrating regenerative agriculture into both operational and reputational strategies. In parallel, environmental and health concerns activate broader engagement by framing regenerative agriculture as a response to ecological degradation and human well-being. Together, these pressures operate across domains but reinforce one another, producing a cumulative effect that expands the field through multiple, overlapping pathways.

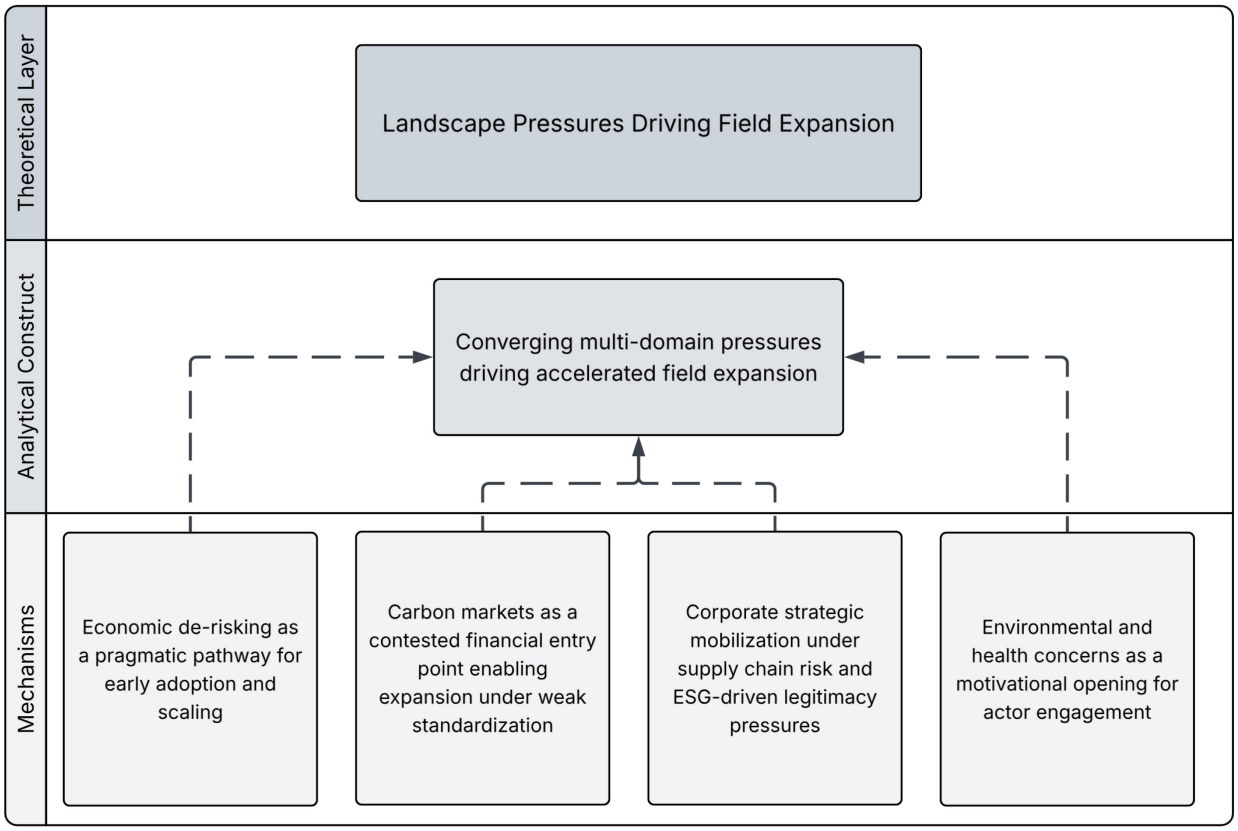


Figure 9: Converging landscape pressures and multiple entry pathways driving field expansion. Mechanisms captured recurring data patterns that were further grouped into higher-order constructs that describe expansion, stabilization, and coordination at the field level. Theoretical layers, in turn, integrated constructs into a broader field-level condition.

Table 9: Mechanisms of field expansion through converging entry logics.

Mechanism	Analytical Role	Empirical Illustration
Economic de-risking as a pragmatic pathway for early adoption and scaling	Enables adoption and scaling by reducing perceived economic uncertainty and input-related costs	"Farmers and ranchers are looking to do de-risk a situation […] Because the whole deal is a gamble" "What often happens […] is end up decreasing inputs, less fuel used, fertilizer use less pesticide use […] and that lowers their costs, and the whole system, like de-risking by itself."
Carbon markets as a contested financial entry point enabling expansion under weak standardization	Enables field expansion by providing financial entry points despite contested standards and low credibility	"Voluntary market sprung up as a way to try to create some kind of a standard around that [accounting and rewarding system]" "Regenerative [has] a big focus is on carbon mitigation […] tying it up to carbon credits is kind of the danger [because] the calculation is not very standardized"

Corporate strategic mobilization under supply chain risk and ESG-driven legitimacy pressures	Enables field expansion by mobilizing corporate engagement under supply chain risk and ESG pressures	"Everyone is pushing [RA] forward because […] they realize that if they don't go in this direction, they won't even have a product to sell" "Having to report our scope three emissions if we're a multinational corporation, requires us to rethink how we are doing our supply chain management"
Environmental and health concerns as a motivational opening for actor engagement	Triggers initial engagement by activating concern-driven motivations tied to environmental and health risks	"There's sort of consequential movement towards this idea [RA] based on the fear of being unhealthy and the environmental concern" "The idea all along has been how do we flip that [environmental impact] to restoring those ecosystems"

This convergence generates a form of accelerated expansion characterized by heterogeneous entry and distributed participation. Actors engage under distinct motivations, including economic viability, financial opportunity, strategic positioning, or normative concern, without requiring shared definitions or standardized practices. As a result, expansion proceeds through multiple, only partially aligned entry logics that enable rapid diffusion across domains. Field growth, in this sense, is not contingent on prior stabilization but is actively driven by the coexistence of these mechanisms, each lowering different barriers to participation. This dynamic establishes the first condition of expansion without stabilization: converging pressures that intensify and diversify participation through parallel pathways of entry rather than through coordinated alignment.

4.2 Institutional Frictions in Field Stabilization

The expansion of regenerative agriculture does not translate into field stabilization because institutional arrangements systematically fail to align with the emergent properties of the field (Figure 10). Rather than consolidating shared standards, coordinating expectations, or enabling convergence, existing governance structures, market dynamics, and policy frameworks introduce persistent frictions that inhibit stabilization (Table 10). These frictions operate across multiple institutional domains, governance, markets, and knowledge systems, and reinforce one another in ways that reproduce dispersion rather than alignment.

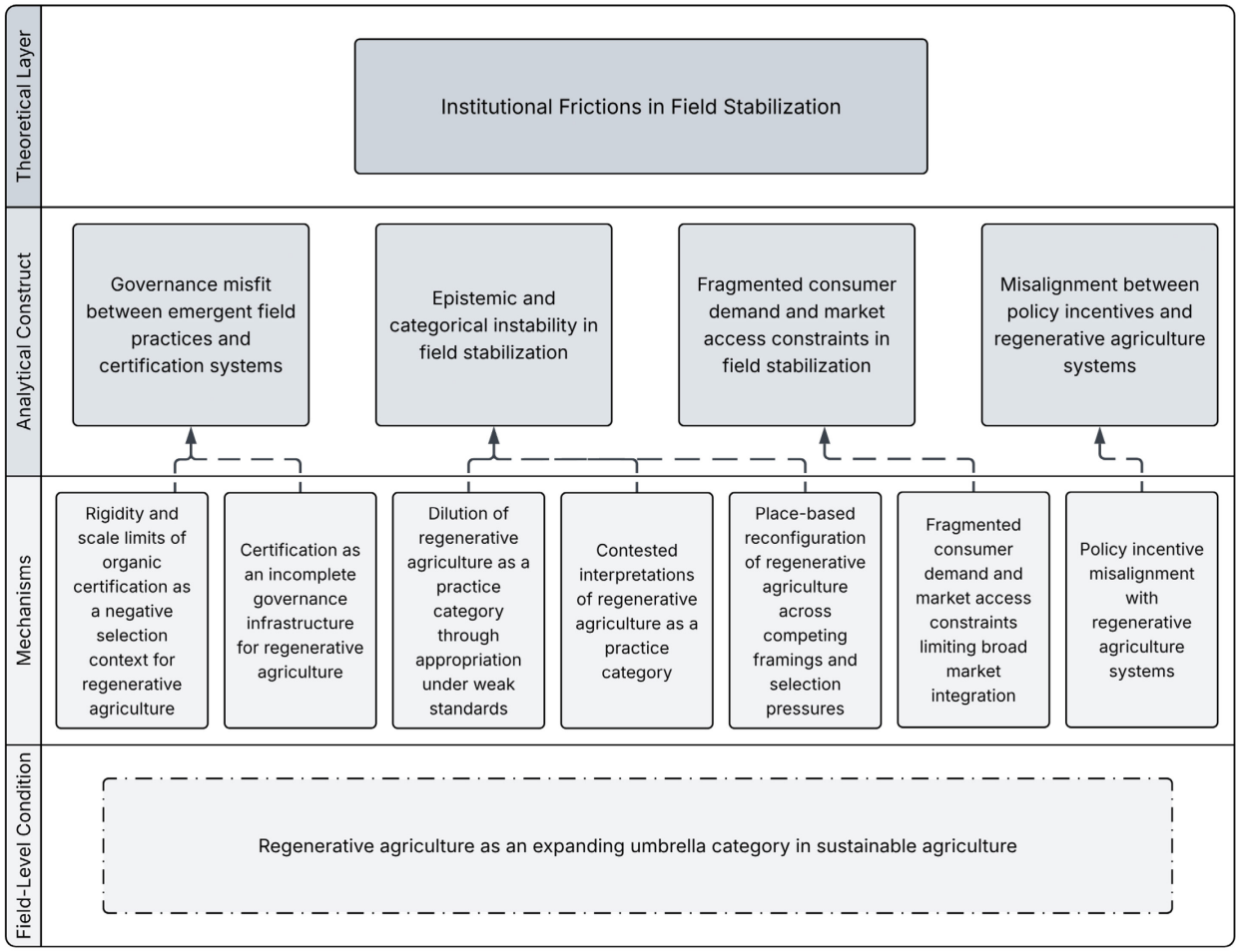


Figure 10: Institutional frictions inhibiting stabilization across governance, markets, and knowledge systems. Mechanisms identified in the empirical material are analytically grouped into higher-order constructs that organize patterns of stabilization across institutional domains. These constructs are subsequently integrated into broader field-level conditions.

Table 10: Mechanisms of institutional frictions inhibiting field stabilization.

Mechanism	Analytical Role	Empirical Illustration
Rigidity and scale limits of organic certification as a negative selection context for regenerative agriculture	Rigid certification baselines misalign with evolving practices, constraining inclusion and inhibiting stabilization	"It's a pragmatic problem, to tie it to organic as a baseline [given that organic is less than 1% of US agriculture]" "[Organic federal law made it] incredibly difficult for auditors and certifiers to actually confirm compliance"
Certification as an incomplete governance infrastructure for regenerative agriculture	Provides partial legitimacy while failing to coordinate and standardize practices	"I think labeling and certifications is one of the biggest challenges in the industry because it creates a lot of consumer confusion" "Having one certification or standard that is like the central one is probably kind of unlikely. I think there is kind of a tension

		between that and the concept of label fatigue”
Fragmented consumer demand and market access constraints limiting broad market integration	Constrains scaling by keeping demand niche and fragmented	“[RA products don't] have as much buying power as they might have expected at this stage" “Whole foods is sort of the only national level retailer for whom I think these sorts of [RA products] move the needle”
Dilution of regenerative agriculture as a practice category through appropriation under weak standards	Enables appropriation, diluting category coherence	“The definition of regenerative ag is a mess. So, companies just implement practices, [and it] doesn't necessarily assure that you're regenerative” “Regenerative agriculture is being used by people who are really trying to do transformative work in the food system, but it's also being used by people who want to continue doing things pretty much the same as they are”
Contested interpretations of regenerative agriculture as a practice category	Creates ambiguity, hindering shared understanding and coordination	“There's this interesting tension going on in regenerative ag between people who see it as a cultural movement versus a set of production practices” “There's a lot of noise in the marketplace […] people saying one thing, they're participating, but in reality, they're really not. And if that wasn't there, we could have more momentum”
Place-based reconfiguration of regenerative agriculture across competing framings and selection pressures	Prevents standardization by producing regional-specific implementations	There are some areas like in New England, Colorado, even Georgia […] that a more holistic approach to regenerative [is] being pursued. In the Midwest, a lot of the regenerative management is more practice based” “[In California] we've the high and the lower end, when it comes to regenerative implementation"
Policy incentive misalignment with regenerative agriculture systems	Constrains adoption and continuity through misaligned incentive structures	“[Incentives are] set up in a way that's very cumbersome and not realistic and more expensive than if they would have just done it on their own" “A lot of the grants are pretty specific […] and wouldn't have the regenerative name attached to it”

First, governance infrastructures, particularly certification systems, impose rigid or partial forms of validation that neither accommodate heterogeneous practices nor establish a coherent baseline for coordination. Second, category-level ambiguity, manifested in the absence of clear and widely accepted definitions, enables divergent interpretations and appropriation, further amplified through regionally distinct implementations. Third, market demand and policy incentives fail to provide consistent and reinforcing signals, remaining fragmented, misaligned, or

insufficiently structured to support convergence. Taken together, these interrelated frictions produce a field in which institutional elements are present but operate in ways that systematically undermine stabilization.

Consequently, stabilization is not merely delayed but actively undermined by the very institutions that might otherwise support it. Instead of facilitating convergence around shared meanings, standards, and practices, institutional arrangements generate selective pressures that privilege localized adaptation over coordinated alignment. This prevents the emergence of a unified category and limits the field's capacity to establish durable forms of governance and evaluation. As a result, regenerative agriculture persists as an expanding but weakly stabilized field, characterized by ongoing ambiguity, uneven implementation, and limited institutional coherence. This condition directly underpins the broader phenomenon of expansion without stabilization, while also creating the conditions for alternative forms of coordination to emerge in the absence of strong institutional alignment.

3.6.3 Provisional Coordination Under Incomplete Stabilization

In the absence of field-level stabilization, coordination in regenerative agriculture does not collapse but is instead reconstituted as a distinct mode of organizing based on provisional and adaptive arrangements (Figure 11). Rather than relying on centralized standards, unified governance, or stable institutional infrastructures, coordination emerges through flexible, distributed, and often temporary mechanisms that enable alignment despite ongoing ambiguity (Table 11). Certification systems are reconfigured to accommodate heterogeneity, shifting away from rigid practice-based compliance toward more flexible and outcome-oriented approaches. At the same time, regenerative agriculture is increasingly framed in terms of measurable outcomes and continuous improvement, providing a basis for comparability even in the absence of standardized practices. Coordination is further sustained through decentralized intermediary activity, where actors translate value across domains and connect otherwise fragmented participants, while incentive programs enable short-term experimentation without requiring long-term institutional commitment. Together, these mechanisms constitute a form of coordination that is functional but inherently partial, sustaining collective activity without generating the consolidation typically associated with field stabilization.

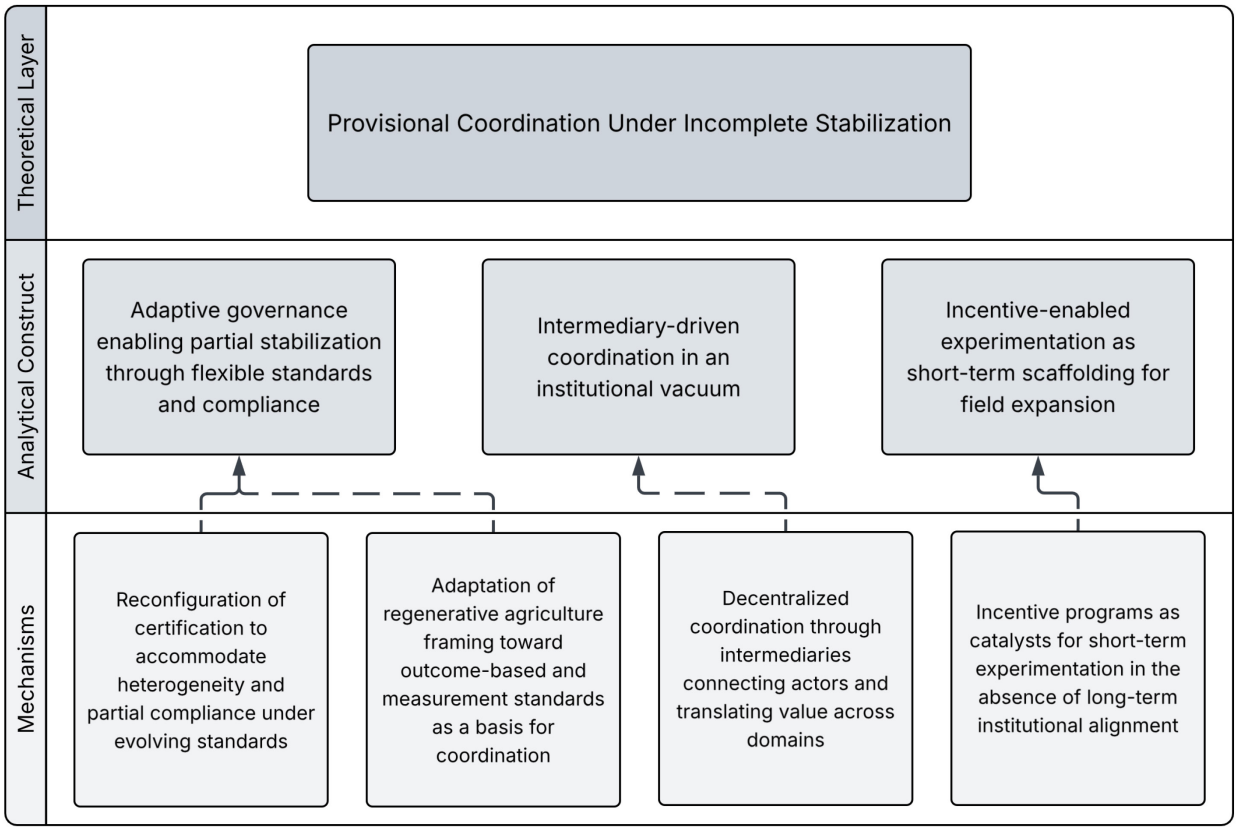


Figure 11: Provisional coordination as an adaptive mode of organizing under conditions of incomplete stabilization. Higher-order constructs derived from empirically anchored mechanisms are integrated into a field-level condition that captures how coordination is sustained under incomplete stabilization.

Table 11: Mechanisms of provisional coordination under incomplete stabilization.

Mechanism	Analytical Role	Empirical Illustration
Reconfiguration of certification to accommodate heterogeneity and partial compliance under evolving standards	Enables coordination despite heterogeneous practices through flexible and outcome-based certification	“Certifications were very practice base, and there's so many limitations to that […] So there's an auto correction happening towards outcomes-based approaches” “The scoring system, is essentially nine ‘yes or no’ questions to the farmer, which can be pretty easily verified, which reduced like a regulatory burden”
Adaptation of regenerative agriculture framing toward outcome-based and measurement standards as a basis for coordination	Enables shared evaluation and coordination through outcome-based framing	"Regenerative is based on […] the idea that you should be having improved outcomes in these factors" “When we talk about regenerative agriculture, we always refer to continuous improvement […] To claim you're practicing regenerative agriculture, your indicators must show improvement”

Decentralized coordination through intermediaries connecting actors and translating value across domains	Enables coordination by bridging actors and translating value in the absence of centralized governance	“What I'm seeing now is people are just going right towards certifications and verifications, and that the organizers are the certifiers and verifiers” "The quick answer is, it's decentralized right now, I'm talking about the entire regenerative agriculture space"
Incentive programs as catalysts for short-term experimentation in the absence of long-term institutional alignment	Enables short-term adoption without long-term stabilization	"It's cool to that some of those benefits do exist, because it helps just kind of recoup […] that cost time and money, that you're just doing out of principle" “But none of those [incentives] support that security for the next five years, and just getting the land to produce more biomass and biodiversity”

As such, this coordination becomes decoupled from stabilization, enabling the field to expand and operate without resolving its underlying institutional fragmentation. Rather than converging toward unified standards or governance structures, regenerative agriculture advances through flexible alignment mechanisms that prioritize adaptability over consistency. This form of coordination supports continued participation and experimentation but does not generate the conditions necessary for durable institutionalization. As a result, the field remains structurally open, with coordination achieved through evolving and provisional arrangements rather than stabilized infrastructures.

3.7 Discussion

I identify a distinct configuration of sustainability transitions, conceptualized as expansion without stabilization. Under conditions of converging pressures, transitions may unfold through a decoupled configuration between expansion, stabilization, and coordination, rather than through sequential alignment and consolidation. In contrast to foundational accounts in sustainability transitions research, where diffusion is associated with increasing alignment across niche, regime, and landscape dynamics and the gradual stabilization of rules, practices, and expectations (Geels, 2002; Geels et al., 2017, 2023; Markard et al., 2012), I show here that expansion can proceed without prior convergence. This configuration is particularly likely under conditions of sustained and interacting landscape pressures, where multiple entry pathways are activated simultaneously and institutional alignment cannot keep pace.

Recent contributions in sustainability transitions research provide useful entry points for interpreting these dynamics, particularly in highlighting how transitions unfold under increasing complexity and urgency. Juntunen and Shakeel (2026) show that policy mixes and contextual interactions shape variation in the pace and form of system change, while Andersen et al. (2026) emphasize the role of accelerating and interacting pressures in driving industrial transformation. Building on these insights, my findings demonstrate that converging pressures do not simply

accelerate transitions but generate multiple and partially independent pathways of entry, enabling expansion without requiring alignment across actors, practices, or institutional domains.

Within this configuration, field stabilization does not fail passively or lag behind expansion. It is repeatedly undermined by institutional infrastructures that reproduce fragmentation across regulatory, market, and epistemic domains. Instead of converging around shared meanings, standards, and evaluative criteria, regenerative agriculture develops under conditions in which ambiguity and contestation are continuously reproduced. Prior research points to key dimensions of this process. Weckowska et al. (2025) highlighted how innovation processes evolve under unsettled institutional conditions, while Schnell and Mattes (2026) showed that legitimacy gaps emerge when new configurations misalign with existing regulatory and normative structures. Similarly, Wesche and Skjølsvold (2025) demonstrated how legitimacy can move across socio-technical boundaries, enabling strategic capture and re-signification. Together, these dynamics indicate that the same institutional arrangements that might otherwise support convergence instead reproduce dispersion, appropriation, and contested evaluation, generating destabilization within the expanding alternative field itself.

Consistent with these conditions, coordination operates independently of stabilization through provisional arrangements. Actors align through outcome-oriented metrics, intermediary translation, and short-term and unsustainable incentives that enable comparability and collaboration without requiring agreement on practices, definitions, or standards. Existing research on intermediaries helps situate these dynamics. Mignon and Bastås (2025) showed how intermediaries translate policy goals into context-dependent practices, while Gaitán-Cremaschi et al. (2024) and Laur and Kanda (2025) highlighted their role in assembling networks and negotiating alignment under conditions of conflict and fragmentation. Extending these works, my findings show that coordination in such contexts is not a pathway toward stabilization but a distinct mode of organizing, in which alignment is continuously negotiated, temporally bounded, and anchored in flexible evaluative criteria rather than fixed institutional frameworks.

All in all, I contribute to sustainability transitions research in three ways. First, I show that converging pressures can drive expansion through multiple and partially independent pathways, enabling diffusion and acceleration without prior alignment. Second, I demonstrate that stabilization is not a natural outcome of expansion but may be actively inhibited by institutional arrangements that reproduce fragmentation within emerging fields. Third, I show that coordination under such conditions is sustained through provisional mechanisms that enable alignment without standardization.

This study is subject to limitations that also point to directions for future research. The empirical analysis focuses on regenerative agriculture, a field characterized by high contestation, multi-actor engagement, and evolving institutional support, which, while theoretically informative, may not fully represent other sustainability transitions. Future research should examine whether similar dynamics emerge across sectors with different institutional configurations. In addition, the analysis provides a cross-sectional account of field development, and longitudinal research is needed to assess how stabilization dynamics evolve over time and whether provisional forms of coordination persist, transform, or coexist with more consolidated arrangements. Finally, findings raise questions about the conditions under which expansion without stabilization evolves under varying degrees of alignment. This calls for further research on how institutional change, governance interventions, and market dynamics shape the potential consolidation of emerging sustainability fields.

3.8 Conclusion

I reconceptualize the relationship between diffusion, stabilization, and coordination in sustainability transitions by identifying a distinct configuration of field development, termed expansion without stabilization. Rather than unfolding through sequential alignment and institutional consolidation, transitions may develop through decoupled dynamics in which expansion, stabilization, and coordination evolve in parallel without becoming fully aligned.
First, my findings show that diffusion is not contingent on prior stabilization. Expansion can proceed through heterogeneous and distributed participation without requiring convergence in meanings, practices, or evaluative criteria. Second, stabilization emerges as a contingent and uncertain process rather than an automatic outcome of diffusion. The consolidation of meanings, standards, and evaluative frameworks may remain incomplete, as institutional arrangements reproduce fragmentation rather than convergence. Third, coordination can be sustained without institutional consolidation through provisional mechanisms that enable alignment without standardization.

Therefore, my findings introduce an alternative interpretation of transition pathways, in which expansion can precede and unfold independently of alignment and stabilization. As such, sustainability transitions may remain structurally open, with expansion, coordination, and institutionalization only partially aligned. Future research should examine how transitions unfold over time under conditions of expansion without stabilization, including the implications of sustained institutional incompleteness for field evolution and regime transformation.

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Concluding Reflections – Organizing with Living Systems

> "*In the natural world, one action or input does not yield one result or output. [A farmer] can't simplify nature's diversity, something industrial agriculture seeks to accomplish with monocultures, a militaristic focus on yields, and human-made substitutions for natural processes."* (Anderson, 2019, p. 72)

One of the defining organizational achievements of the twentieth century was the transformation of agriculture into an industrial enterprise. As Deborah Fitzgerald describes in *Every Farm a Factory* (2003), agricultural production increasingly came to be organized according to the principles that had reshaped manufacturing: specialization, standardization, predictability, mass production and efficiency. Farms were reconceived not simply as ecological systems, but as productive units whose performance could be improved through technological intervention, managerial control, and the systematic reduction of variability. This transformation helped support unprecedented increases in agricultural productivity and played a central role in feeding a rapidly growing global population.

Yet the same organizational logic that contributed to these achievements also introduced a persistent tension. Industrial systems function best when complexity can be reduced, uncertainty minimized, and outcomes rendered predictable. Living systems, however, rarely operate under such conditions. Soils, plants, water cycles, microorganisms, and climatic processes interact through relationships that are dynamic, context-dependent, and often resistant to simplification. As Anderson observes, nature does not respond through the linear cause-and-effect relationships that industrial systems often seek to impose. Ecological processes generate multiple outcomes simultaneously, unfold across different temporal scales, and continuously adapt to changing conditions.

This dissertation began from the observation that regenerative agriculture has emerged as one response to this tension. While often presented as a collection of agricultural practices or environmental outcomes, regenerative agriculture also represents a broader attempt to reorganize agricultural production around ecological processes rather than around the simplification of those processes. In many respects, the questions examined throughout this dissertation ultimately converge on a larger issue: what happens when the organizational principles that have historically guided conventional agriculture encounter the realities of living systems?

The analyses presented in this dissertation suggest that this encounter extends well beyond regenerative agriculture itself. If industrial agriculture was built upon the aspiration to reduce variability, simplify complexity, and render production increasingly predictable, the findings presented here indicate that many sustainability challenges emerge precisely where such aspirations encounter the realities of living systems. The three chapters examine how this tension unfolds across organizational practices, material outcomes, and field development.

The first chapter contributes to routine dynamics by advancing a more explicit account of how ecological processes participate in the formation and stabilization of organizational routines. While recent scholarship has encouraged greater attention to materiality and more-than-human participation in routines (Feldman & Pentland, 2022; Xu & Carlile, 2024), the concept of ecological routines demonstrates how recurrent patterns of action emerge not through the

replication of standardized practices but through continuous adaptation to responsive ecological conditions. In doing so, the chapter also responds to broader calls within sustainability transitions research to better connect macro-level accounts of system change with the micro-level dynamics through which alternative practices emerge and persist (Geels et al., 2023; Keller et al., 2022; Koistinen & Teerikangas, 2021).

The second chapter contributes by providing a material account of regenerative agriculture's environmental performance through field-scale estimates of consumptive water use. Rather than assuming that improvements in one ecological process necessarily translate into others, the analysis shows that regenerative management does not systematically increase evapotranspiration relative to conventional systems, while also illustrating the context-dependent character of these relationships. In doing so, the chapter advances ongoing discussions surrounding the evaluation of regenerative agriculture by shifting attention from generalized sustainability claims toward empirically specified environmental outcomes (Lankford & Orr, 2022). More broadly, it reinforces emerging perspectives within sustainability transitions research that expectations surrounding alternative systems require continuous empirical validation as sustainability claims become increasingly central to their legitimacy and diffusion (Geels et al., 2023; Lempiälä et al., 2019).

The third chapter contributes to sustainability transitions research by examining the relationship between field expansion and institutional stabilization. Drawing on the case of regenerative agriculture, it shows that rapid field expansion can occur without corresponding convergence around shared governance arrangements, standards, or evaluative frameworks. This finding qualifies recent discussions on transition dynamics by suggesting that institutional stabilization should not necessarily be understood as a prerequisite or parallel process to field expansion, particularly in rapidly evolving sustainability domains (Andersen et al., 2026; Geels et al., 2023; Markard et al., 2020).

Beyond their individual contributions, the three chapters reveal a common pattern. Whether examining the formation of regenerative practices, their environmental outcomes, or the development of regenerative agriculture as an emerging field, ecological complexity repeatedly exceeded attempts to fully standardize, predict, and organize it. Stability proved less a consequence of simplification than of continual adaptation to ecological and institutional conditions.

If this observation holds, then its implications extend beyond regenerative agriculture itself. Many of the environmental challenges confronting contemporary societies are commonly approached as problems of technological innovation, policy design, market incentives, or institutional arrangements. While these dimensions remain undeniably important, my findings suggest that sustainability challenges are also fundamentally organizational in nature. Whether in agriculture, ecological restoration, water governance, or other forms of environmental management, the task is rarely limited to producing desirable ecological outcomes. It also involves developing ways of organizing human activity that remain responsive to systems characterized by uncertainty, interdependence, and continual change. In this sense, the challenge of sustainability may not lie solely in changing what we do, but in rethinking how we coordinate, evaluate, and sustain action under ecological conditions that resist simplification.

Perhaps the broader lesson emerging from this dissertation is that sustainability transitions are often imagined as a search for better solutions, when they may equally be a search for different relationships with complexity itself. For more than a century, modern societies have achieved remarkable gains in productivity and material wellbeing by developing increasingly sophisticated ways of simplifying, standardizing, and controlling the world around them. Yet living systems

continue to remind us that not all complexity can be eliminated without consequence. Soils, plants, water, and climate do not respond as components in a machine. They interact, adapt, and change through relationships that remain only partially visible and never fully controllable. If regenerative agriculture offers a lesson beyond farming, it may be that the pursuit of sustainability requires organizing human activity in ways that remain attentive to the complexity of the systems upon which it ultimately depends.

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