Measuring the Maturity of Technology-Based Innovation Ecosystems

Chloe Adams[1], *Olga Pierrakos, Ph.D.[2],
* *Corresponding Author: pierrao@wfu.edu*

[1] *Department of Engineering, Wake Forest University,* Winston-Salem, USA

[2] *Department of Engineering, Wake Forest University,* Winston-Salem, USA

***Abstract*— Innovation ecosystems have emerged as a focal point of research and policy, as their central role in technological advancement, economic growth, and societal progress becomes widely recognized. Despite this growing attention, the existing literature attempting to identify key ecosystem components remains fragmented. Often examining these indicators in isolation, researchers fail to treat innovation ecosystems as the interconnected wholes they are. This gap limits the ability of policymakers, practitioners, and other stakeholders to understand ecosystem development and to holistically assess ecosystem performance across regions. Drawing on a comprehensive review of relevant literature, ten Innovation Ecosystem Critical Elements (IECEs) were identified across structural, institutional, and relational dimensions. As examples, two of these critical elements include human capital, capturing the availability and development of ecosystem inhabitants, and regulation and policy, which encompass the governance structures that shape innovation incentives and constraints. Using these elements, we propose a framework for measuring innovation ecosystem maturity, conceptually mirroring NASA's Technology Readiness Levels (TRLs), but aiming to offer Innovation Ecosystem Maturity Levels (IEMLs). While other score-based approaches to innovation ecosystem evaluation have been proposed, this contribution adopts a normative and accessible design for a wide range of uses by organizations, government, and individuals. We offer two use cases as part of this paper, and these use cases target two geographic regions representing different maturity profiles. A comparative gap analysis of maturity demonstrates how the framework offers new insights that can guide both users and researchers. Strengths and shortcomings will be presented in the use of the framework as well as future work. This study contributes an adaptable, practical tool for benchmarking innovation ecosystems and informing policy decisions.**
Keywords*— *Innovation Ecosystem; Technology; Quadruple Helix; Innovation Maturity

I. INTRODUCTION

Research on innovation ecosystems continues to expand as scholars and policymakers increasingly recognize that innovation does not happen in isolation. Innovation ecosystems are the interconnected networks of various actors from universities to investors and government institutions that collectively take part to enable technological advancement and innovation [1]. Through these interactions, innovation serves as the vehicle by which societies experience economic growth, job creation, and improved health outcomes. Unlike other policy interventions, these effects are not short-lived or fleeting, with innovation repeatedly found to be a driver of long-run, sustained economic growth [2]. Amidst debate about the most precise definition of innovation ecosystems, there is broad agreement that there exists several elements that every ecosystem needs to develop and mature. While research has advanced our understanding of these elements, the challenge is that they are often examined in isolation or a few at a time rather than as a collection. Few studies feature a holistic view of innovation ecosystems and often not providing a wide-ranging exploration of ecosystem components. As a result, a developmental framework is missing in this research area.

In this paper, we propose a framework for assessing innovation ecosystem maturity based on ten critical elements identified across relevant literature, which will hereafter be referred to as Innovation Ecosystem Critical Elements (IECEs). While other approaches to innovation ecosystem evaluation have been proposed, they typically rely on complex calculations and extensive datasets that may limit accessibility for policymakers and practitioners. This study provides a normative and accessible design useful for a wider audience, in which development stages are emphasized as opposed to numerical ranking. We conceptually model our framework after NASA's Technology Readiness Levels (TRLs), a nine-parameter measurement system that evaluates the degree of technology development against success criteria. TRLs range from TRL 1, the basic research stage, to TRL 9, full-scale operation proven [3]. Originally developed in the 1970s, the TRLs are part of NASA's broader technology readiness assessment, where they are used to inform resource allocation decisions and risk management [4]. With each level increase, the rigor of integration testing and validation rises as well. Attaining widespread usage, the TRLs maintain prevalence due to their broad applicability and simplicity. This established evaluation system yields a valuable basis for structuring innovation ecosystem progression. Instead, we offer Innovation Ecosystem Maturity Levels (IEMLs) to capture developmental trajectory, allowing users to identify the strengths and shortcomings of a target ecosystem. To demonstrate the application of our framework, we examine two geographic case studies, the Greater Boston region of Massachusetts and the Piedmont-Triad region of North Carolina, showing the differences between higher and lower-developed innovation ecosystems. **To guide the development of the proposed framework, the following research questions (RQs) are posed: (<u>RQ1</u>): What**

components commonly appear across innovation ecosystem literature? (RQ2): How can these components be integrated into a maturity-based framework for evaluating ecosystem development? (RQ3): How do innovation ecosystem maturity profiles differ across two distinct regions?

II. LITERATURE BACKGROUND

Within this context, the Triple and Quadruple Helix models are the most widely referenced innovation frameworks [5]. In innovation ecosystem studies, these frameworks serve as conceptual foundations and methodological guides for explaining actor interactions. The Triple Helix describes the interactions between academia, industry, and government in fostering innovation and technological progress [6]. Developed by Carayannis and Campbell (2009), the Quadruple Helix model adds civil society as the fourth dimension, reflecting the growing emphasis on community-driven and socially responsible innovation. Accordingly, this study adopts the Quadruple Helix framework as the conceptual basis for evaluating innovation ecosystems.

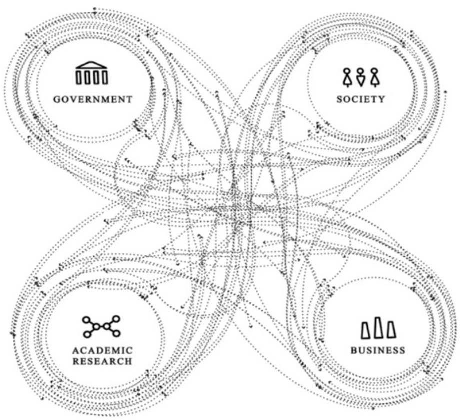

Figure 1. Quadruple Helix Innovation Model [8]

Across the literature, several recurring components appear in mature innovation ecosystems. These IECEs, summarized in Table I, can be organized into three categories: structural, institutional, and relational. Consensus has emerged among scholars around a number of structural factors that provide foundational resources for innovative activity. **Human capital** underpins innovation, encompassing the abilities and skillsets of the individuals in an ecosystem. Highly educated workforces in Science and Engineering (S&E) and well-funded professional training and university programs play an essential role in knowledge generation and diffusion [9]. Dependent on human capital, diverse **infrastructure** enables the connectivity required within an ecosystem. Physical infrastructure, such as roads and power grids, connects people and spaces, while digital infrastructure establishes the reliable communication pathways that permit knowledge exchange. Incubators, hubs, and intermediaries represent the functional infrastructure that facilitate innovation and commercialization [10].

Furthermore, the literature emphasizes the importance of **financial capital** and **market access** in fueling R&D and recruiting talent to an ecosystem. Financing may be either public or private, with venture capitalists and government initiatives, such as the SBIR/STTR program, both acting as primary funding sources for entrepreneurs [11]. In turn, scholars pinpoint financial market access as critical for entrepreneurs in identifying opportunities to finance and commercialize innovative outputs [12]. Constructing a market that is attractive to innovators and investors largely depends on the regulatory framework of an ecosystem.

Institutional components exert a significant influence on the degree to which innovation can be propelled. **Regulation** reaches across economic, social, and institutional domains, sculpting innovation incentives and constraints in different ways. In particular, patents play a central role in incentivizing innovation by granting inventors temporary exclusive rights, but are balanced by anti-monopoly laws. The regulatory environment of an ecosystem also shapes business creation and investment conditions. In parallel, institutional **leadership** (e.g., government, firms, and universities) fashions the policies and regulations that subordinates must abide by, and these decisions directly impact innovation capacity [13]. Leaders have the power to set the direction of their ecosystem, mobilize resources, and steer stakeholders and subordinates toward goals [14]. However, **collective commitment** from actors across an ecosystem — employees, faculty, community members — must complement good leadership to translate vision into desired outcomes.

Relational elements entail the components whose primary value emerges from the connections they enable among ecosystem actors. **Networks** are widely viewed as essential to knowledge exchange, accessing new markets, and pooling skills [15]. Closely related, **collaboration** has been instrumental in innovation-intensive industries, particularly within the rapidly evolving biotechnology and computer industries, where it takes much coordinated effort from many actors and stakeholders to bring discoveries to market [15]. Beyond formal collaboration, **culture** is likewise central to the capacity of an innovation ecosystem, as certain cultural norms (e.g., openness, autonomy, individualism) influence the innovative climate within an organization or region [16].

While prior studies frequently reference structural and institutional influences and relational dynamics, the elements are seldom organized into a unified framework. To the best of our knowledge, the three categories presented in Table I offer a systematic way to bring these components into a single framework.

TABLE I. INNOVATION ECOSYSTEM CRITICAL ELEMENTS (IECES) IDENTIFIED ACROSS THE LITERATURE

Structural	***Institutional***	***Relational***
Human Capital	Regulation & Policy	Networks
Infrastructure	Leadership	Collaboration
Financial Capital	Collective Commitment	Culture
Market Access	--	--

III. METHODOLOGY

To answer the research questions, this study uses a qualitative and multi-step approach. First, ten IECEs were identified through a review of existing literature, and these elements formed the basis of the proposed framework. From there, an evaluation of two regional innovation ecosystems was conducted to evaluate its utility across stages of maturity.

A. *Scoping Review and IECE Identification*

The scoping review of the literature and identification of IECEs was conducted by a single investigator. The initial step of the review was identifying relevant studies on innovation ecosystems and identifying elements critical to their development. Peer-reviewed articles published in English-language journals and government documents were used to identify highly cited and relevant works. Studies focusing on highly localized case studies without broader innovation ecosystem implications were excluded. Studies published before 1995 were excluded in an effort to reflect contemporary innovation ecosystem dynamics. A total of twelve articles spanning economics, business, and innovation policy journals were included in the scoping review.

While reviewing candidate articles, ecosystem components were identified. As these components emerged, targeted searches were conducted to determine their relevance and prevalence in innovation ecosystem research. Keywords such as "[element] and innovation," "[element] and innovation performance," "[element] impact on innovation," and "measuring [element]" were used in the search. This iterative search process served to ensure that the IECEs were consistently covered in the literature. The resulting list of elements was reviewed by the project supervisor to confirm that the IECEs were supported by the selected sources.

B. *Framework Development and Measurement Approach*

Adapting the logic of the NASA Technology Readiness Levels, an innovation ecosystem development scale was the guiding goal. Tracking ecosystem maturity across seven levels, the IEMLs conceptualize development relative to innovation output, coordination among actors, and the availability of resources. The framework comprises seven levels to balance practical interpretation against analytical rigor. This number of levels allows for meaningful distinctions between early-stage, regionally competitive, and dominating ecosystems to be made without overcomplication. The stage definitions were informed by recurring patterns from across innovation ecosystem literature. Lastly, the IECEs guided the evaluation process, in which the strength of each element was assessed through commonly reported metrics, such as R&D investments and expenditures devoted to human capital development.

C. *Case Study Evaluation*

In applying the proposed framework, two innovation ecosystems were selected for this study: The Greater Boston region of Massachusetts and the Piedmont-Triad region of North Carolina. The selected regions were chosen as they represent contrasting stages of innovation ecosystem development. Boston is commonly recognized as a highly developed ecosystem, while the Piedmont-Triad region is an earlier-stage ecosystem that has recently gained attention through the National Science Foundation's Innovation Engines program [17]. Further, the Piedmont-Triad region is home to Wake Forest University, the institutional setting of this research, so it provided a locally relevant case. Publicly available indicators and metrics related to the IECEs, such as the Massachusetts Innovation Index and the North Carolina Innovation Index, were collected from government sources and peer-reviewed articles. The indicators included measures of financial capital, namely, venture capital investment and of institutional activity, reflected in patenting and academic licensing revenue. These were used to qualitatively assess the development of each ecosystem and map it to the corresponding IEML. The maturity profiles were compared across two cases to examine differences in innovation ecosystems development.

IV. INNOVATION ECOSYSTEM MATURITY FRAMEWORK (IEMF)

This section presents a framework for innovation ecosystem maturity, building upon the identification of the IECEs (Table I) and their integration into a maturity-based structure (Table II). As previously noted, the proposed framework draws inspiration from the Technology Readiness Levels (TRLs) developed by NASA to benchmark technology progression. The TRLs provide a structured framework for determining the maturity of a technology from basic research to mission-proven. Capped at nine levels, the expectation of key technological factors (e.g., level of integration, fidelity of build) intensifies as TRLs increase [3]. Our framework offers a tool to assess innovation ecosystem maturity that, too, emphasizes developmental trajectory over performance rankings. The IEMLs range from latent, existing but atrophied ecosystems, to globally competitive hubs of innovation. Each maturity level is defined by the presence and development of specific IECEs (Table I), which are explicitly mapped across the structural, institutional, and relational dimensions in Table II. As maturity advances, the expectations for the dimensions become more robust. Levels consider the IECEs in combination, as innovation capacity is dependent upon the interaction of multiple elements.

The levels show a progression where innovation ecosystems evolve from fragmented and underdeveloped environments to highly developed interconnected systems. To evaluate maturity, IECEs were assessed according to commonly used indicators from publicly available sources. These indicators were qualitatively used to determine IECE strength and characterize ecosystem development. Ecosystems at different levels exhibit varying degrees of IECE strength and integration.

IEML 1 ecosystems have few research institutions and very limited innovation-capable human capital, with most of the population engaged in artisanal or manual occupations. Physical infrastructure may be sufficient, but broadband connection and other digital infrastructure are underdeveloped. Functional infrastructure, such as incubators or accelerators, is missing or sparse. These ecosystems do not attract much financial capital and will have negligible venture investment. The market is neither widely accessible nor developed, directly impacting entrepreneur attraction. Regulation strains or does not encourage innovation, and leadership struggles to create successful innovation-inducing programs.

TABLE II. IEML DEFINITIONS AND DEVELOPMENT CRITERIA

IEML	*Descriptor*	*Structural*	*Institutional*	*Relational*	*Development Criteria*
1	Latent	Low human capital; weak infrastructure	Weak policy and leadership	Sparse networks	Limited workforce in science and engineering, weak research institutions, minimal collaboration
2	Nascent	Developing infrastructure; early human capital growth	Emerging policy support	Initial networks forming	Developing infrastructure and institutional support, limited startup activity
3	Emerging	Growing financial capital; functional infrastructure	Strengthening policy support	Expanding networks and collaborations	Growing knowledge outputs, early formation of functional infrastructure and collaboration networks
4	Expanding	Increasing financial capital; improving market access	Coordinated policy and leadership	Active collaboration networks	Stronger research institutions and talent recruitment, increasing presence of venture capital
5	Regional Hub	Strong human capital; robust financial capital	Established policy and leadership	Dense networks; strong collaboration culture	Significant startup and venture activity, denser networks, strong university research base
6	National Leader	Advanced infrastructure; high capital investment	Strong regional and national policy alignment	Highly integrated networks	Strong talent recruitment, high R&D investment and venture capital presence
7	Global Hub	World-class infrastructure; global market access	Globally competitive institutions	International collaboration networks	World-leading firms and universities, attraction of global investments

As such, weak institutional leadership renders collective commitment futile. Relationally, ecosystem culture does little to escalate innovation. Networks are fragmented, and opportunities for collaboration scantly arise. This type of inactive innovation ecosystem is best described as latent.

IEML 2 ecosystems are no longer dormant; development has been set in motion, but the process is in its earliest stages. Foundational investments in S&E begin to emerge, reflected in increased educational emphasis and workforce interest. However, inputs have not translated into measurable outcomes. Infrastructure is improving, with now developing research centers that are supported through improving intermediary activity. Financial capital remains sparse, and the market is still underdeveloped. Regulation and policy may be shifting to increase innovation, and leadership may have set a strategic vision for their ecosystem, but tangible impacts are not yet evident. Initial collaboration has begun, but networks are still loosely connected. Cultural attitudes are becoming more receptive to inventiveness and creativity.

Transitioning from the nascent stage, **IEML 3** ecosystems are now experiencing tangible improvements and are emerging as viable innovation ecosystems. The inputs have produced outcomes: more ecosystem inhabitants are entering S&E occupations and principal infrastructure is in place. Physical and digital infrastructure are mostly to fully developed. Functional infrastructure is present and operating at a satisfactory level. While venture capital opportunities may still be limited, financial capital is more accessible, and government programs, such as SBIR & STTR, are fueling further growth. Institutionally, the initial effects of policy changes manifest through growing knowledge outputs and increasing patenting activity. Leadership is keeping subordinates on track to accomplish innovation objectives. Networking events and collaboration spaces increase, and ecosystem inhabitants adopt norms conducive to local innovation.

Once innovation activity accelerates, an ecosystem can be classified as **IEML 4**. There is notable participation in S&E occupations, and digital and physical infrastructure have minor limitations. The ecosystem is starting to attract skilled talent, and innovation outputs are generated at above-average levels. The ecosystem is increasingly identified as having commercial potential, which leads to growth in venture capital and startup activity. Still, funding is not abundant. Market access is improving, providing opportunities for producers and consumers. The policies set by leadership are yielding the intended results, and commitment is strong. There is more frequent collaboration and interaction between actors, although these connections might not be high impact yet.

IEML 5 ecosystems stand out regionally for their innovation capacity. Structural elements are fully developed, with strong human capital pipelines supporting regionally recognized universities and research bases. Physical, digital, and functional infrastructure might only require incremental improvements but not foundational changes. There is active venture capital presence, along with regionally competitive startup formation and incubator networks. At the institutional level, the regulatory framework and leadership practices are effective. Further, the ecosystem has dense networks and frequent collaboration. However, collaboration and influence are mostly focused within regional and sometimes national boundaries.

IEML 6 ecosystems are national leaders in innovation, with globally ranked universities and a diverse but also specialized workforce. These ecosystems attract plenteous financial capital and significant private investment with increasing participation from international investors. Accompanied by a highly innovation-friendly regulatory environment, startup and patenting activity is among the highest in the nation. Networks span beyond regional boundaries, and collaboration extends into multiple sectors. IEML 6 ecosystems may exhibit an outward-facing culture but have not reached dominant, global influence.

Few ecosystems achieve **IEML 7**, as this level requires sustained and globally dominant innovation activity. To begin, the human capital within IEML 7 ecosystems is world leading. Though improvements to infrastructure are not needed, it is always evolving to generate cutting-edge research and large-scale commercialization. These ecosystems consistently produce high impact tech adopted around the world. This is seen through their extensive patent portfolios that have top rates of patent families.

Financial capital is globally sourced, and knowledge spillover occurs across industries and geographical boundaries. Networks at this level serve as exemplars for all other ecosystems, and an opportunity to collaborate within them is highly sought after. Accelerator programs and technology-related networking events have global reach, attracting the most skilled talent in the world. Culturally, these ecosystems are highly entrepreneurial and globally oriented, encouraging risk-taking and experimentation. Though not every ecosystem maps perfectly to an IEML, the best classification should be assigned.

V. CASE STUDIES

The Greater Boston region of Massachusetts and the Piedmont-Triad region of North Carolina will serve as case studies to represent a preliminary application of the IEMF.

A. The Greater Boston Region of Massachusetts

The Boston metropolitan area greatly benefits from its globally acclaimed research institutions. Home to Harvard University, the Massachusetts Institute of Technology, and Boston University, these universities attract and retain top talent in business and technology [18]. The industries represented in this ecosystem are diverse, and yet, there is a clear specialization in healthcare and life sciences, especially biotechnology. Displaying structural and relational interdependence, Boston provides endless opportunities for its businesses, which include hundreds of startups, to collaborate and network [18]. This is made possible through features such as the Cambridge Innovation Center, Venture Café, and MassChallenge — a global startup accelerator. Moreover, Boston is consistently identified as a top city for venture capital investment globally, demonstrating unmatched financial capital and market access [18]. Innovation is heavily supported by Boston's institutional elements. A leading generator of technology patents per capita, the Massachusetts regulatory environment masterfully balances incentive and constraint [19]. Knowledge creation and commercialization are further reinforced by exceptional governance. Formed in 2010, the Mayor's Office of New Urban Mechanics (MONUM) has built partnerships across the quadruple helix, intentionally targeting increased civic engagement and racial equity [20]. Effective leadership is specifically shown in the strategic partnership between a former mayor and IBM to launch StartHub, a digital network platform for startup development, and the negotiation by the city government to acquire the space for MassChallenge [20, 21]. Taken together, Boston exhibits rarely paralleled strength across all IECEs. Accordingly, these characteristics suggest that Boston most closely aligns with IEML 7.

B. The Piedmont-Triad Region of North Carolina

Consisting of twelve counties, the Piedmont Triad region is referred to as the "heart of North Carolina." Wake Forest University and N.C. A&T University are among the higher education institutions that have raised the ecosystem's university R&D/GDP to above 50% of the national average [12]. Despite standout research activity, the workforce has historically concentrated in furniture, textile manufacturing, and tobacco. However, leadership has articulated a clear vision for workforce development and industry cluster growth [22]. In addition to receiving almost a quarter of the state's SBIR/STTR funding, the Piedmont Triad region was recently selected for the NSF Regional Innovation program [23]. Already awarded $15 million, the grant aims to advance regenerative medicine and create high-impact commercial products in the area. Still, access to financial capital remains a key constraint, though private sector engagement is increasing. With an international airport and multiple interstate highways, physical infrastructure is well-developed [22]. In contrast, broadband access and fiber availability vary significantly throughout the ecosystem [22]. Striving to build "connective tissue," the Triad is addressing fragmentation across its primary metropolitan areas: Greensboro, High Point, and Winston-Salem. Finally, positive cultural attitudes toward innovation are evolving, as the region invests in partnerships to create an entrepreneurial-minded and global-oriented workforce [22]. Demonstrating clear advancements in multiple IECEs, the presence of active research, growing institutional coordination, and early commercialization efforts push the Piedmont Triad ecosystem to IEML 4. These initial assessments display the framework's potential, but a more thorough and systematic investigation is needed for full validation.

TABLE III. IEML PRELIMINARY ASSESSMENT OF CASE STUDY REGIONS

Region	*Structural*	*Institutional*	*Relational*	*IEML*
Greater Boston	Strong: advanced human capital and infrastructure, top-tier universities, high VC investment,	Strong: supportive policy, active leadership, commercialization support and high patenting	Strong: frequent collaboration opportunity, dense networks, innovation inducing culture	7
Piedmont -Triad	Developing: growing R&D base, improving infrastructure, but limited VC	Emerging: increasing coordination, increasing policy and government support	Developing: fragmented but improving networks	4

As shown in the table above, the Greater Boston and Piedmont-Triad regions exhibit visible differences in maturity when considering the IECE categories. This first attempt at mapping the framework illustrates how the IEMF can be deployed to determine whether an ecosystem is in earlier or later stage development through analysis of key characteristics.

VI. DISCUSSION & CONCLUSIONS

The proposed Innovation Ecosystem Maturity Framework organizes ecosystems into seven levels, providing a structured approach for measuring ecosystem development through the integration of key components. The lower levels are characterized by fragmented structures and limited financial investment, along with limited knowledge outputs and product innovations. Alternately, the higher levels feature the IECEs working in cohesion to increase resource access and ultimately sustain innovative activity. The case studies show how the framework serves to distinguish between ecosystems at different stages. The Piedmont Triad reflects an ecosystem in transition, as its strategic partnerships and improving infrastructure position it to be regionally competitive in the near future. On the other hand, Greater Boston represents a fully integrated ecosystem operating at the highest level. Together, these cases emphasize the distinction between input-driven and output-driven development. The implications of this investigation are many. For policymakers, this framework acts as a diagnostic tool. The framework can be used to inform policy decisions, allowing for gaps and strengths to be identified across ecosystem components. Researchers and practitioners may find value in the cross-case analysis that this standardized system provides. Further, regional planners and economic development groups can use the framework to benchmark progress over time and inform strategic investments. Ultimately, more research is needed to further validate this preliminary IEML framework.

Despite its uses, the framework has limitations. The qualitative nature of the framework means evaluation depends on the interpretation of the investigator. Additionally, a lack of data availability may affect accurate assessment. Future research should involve strengthening the objectivity of the framework by incorporating commonly used quantitative indicators for each IECE. Extending its application to an even wider selection of innovation ecosystems would further validate the framework's robustness. Overall, this framework proposal offers a scalable foundation to analyze and advance innovation ecosystems.

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