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The Bioeconomy—A New Life Cycle Phase For Swedish Forestry

Evidence from 50 Years of Significant Innovation Output

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This paper examines forest-based bioeconomy innovation in Sweden between 1970 and 2021 to test central claims about innovation complexity, knowledge requirements, collaboration intensity, and industrial life cycle dynamics. Using a comprehensive database of 4,972 commercialized innovations, I identify 649 forest bioeconomy innovations and analyze their characteristics through logistic regression, count statistics, and qualitative assessment of innovation biographies. The analysis reveals a structural transformation around 1990, marking a shift from component optimization (1970–1989) focused on mechanization to product expansion (1990–2021) emphasizing novel bio-based products. This transition aligns with industry life cycle rejuvenation: established firms maintained dominance, shifting from adopting external innovations to producing them internally. Contrary to prevailing assumptions, bioeconomy innovations were associated with lower developmental complexity and narrower knowledge bases than other innovations. Public funding's association reversed from positive pre-1990 to negative post-1990. Collaboration intensity showed no association before 1990 but became positively associated with bioeconomy innovation during the product expansion period, providing partial support for the bioeconomy literature's emphasis on collaborative development. These findings challenge expert consensus about bioeconomy innovation requirements and demonstrate that mature resource industries can undergo competence-enhancing transitions without creative destruction. Results indicate bioeconomy policy effectiveness depends critically on recognizing life cycle stage differences rather than assuming universal innovation characteristics.

Keywords: Industry Life Cycle, Bioeconomy, Innovation, Forest Industry, Industry Rejuvenation, Sweden

JEL Codes: O31, O33, L73, L16, Q23

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1 Introduction

Forest industries have been central to Scandinavian economic development since the late 19th century, transforming Finland, Sweden, and Norway from economic peripheries into industrial economies (Lehtinen et al., 2016). By the late 20th century, Nordic forestry had matured—harvest levels plateaued, production processes optimized, and international competition intensified (Peterson, 2001). By 2030, European pulp and paper firms expect 40% of their turnover to come from entirely new bio-based products (biofuels, textiles, biochemicals) rather than traditional paper (Toppinen et al., 2017). Such products are part of the larger ambition to create an economy based on renewable biomass rather than fossil resources, broadly referred to as a bioeconomy (Bröring et al., 2020; Bugge et al., 2016). This strategic shift poses a fundamental question for the mature industry: will the transition to a bioeconomy require creative destruction of existing capabilities within forestry, or can its incumbents leverage accumulated knowledge to expand product spaces?

Two literatures offer contradictory predictions. Industry life cycle theory expects mature resource industries to optimize existing processes through external suppliers, with new entrants driving radical product shifts (Hayter and Edenhoffer, 2016; Klepper, 1996). Bioeconomy scholars argue the opposite: successful bio-based innovation requires fundamentally greater complexity than conventional innovation, demanding broad cross-sectoral collaboration, diverse knowledge bases, and substantial public funding (El-Chichakli et al., 2016; Golembiewski et al., 2015; Issa et al., 2019; van Lancker et al., 2016). These claims shape Nordic bioeconomy strategies (Högbom et al., 2021; Holmgren et al., 2022) but rest on expert opinion rather than evidence from commercialized innovations.

This paper examines 649 forest-based bioeconomy innovations commercialized in Sweden between 1970 and 2021 to test these competing claims. I find that Swedish forestry underwent competence-enhancing rejuvenation around 1990—incumbents shifted from adopting external process innovations to producing novel bio-based products themselves. However, contrary to bioeconomy literature assumptions, successful bioeconomy innovations were associated with lower developmental complexity, narrower knowledge bases, and (after 1990) less public funding than other innovations. The transition built on focused biomass processing expertise rather than broad interdisciplinary collaboration.

The main data source is a database of significant Swedish innovations built on the literature-based innovation output method (Kander et al., 2019; Sjöö et al., 2014), containing 4,972 commercialized innovations collected from independent and edited trade journals. All innovations were recently linked to public funding applications by Fink and Taalbi (2024). Additionally, I collected commodity price data for oil and wood, to account for likely market incentives that could provide directionality to innovation.

Three findings emerge from analyzing innovation output patterns, firm-innovation entry-exit dynamics, and logistic regression on innovation characteristics. First, Swedish forestry transitioned around 1990 from a component optimization period (1970–1989), where external suppliers provided modular mechanization improvements, to a product expansion period (1990–2021) where incumbents increasingly produced integrated systems and novel bio-based products. Annual bioeconomy innovation output remained broadly stable across the period, but its character and sectoral locus shifted. Second, within core forestry sectors, this transition aligned with industry life cycle rejuvenation rather than creative destruction. Established forest sector firms drove product expansion, leveraging accumulated biomass processing knowledge. New entrants surged during crisis periods (1970s oil shocks, 2000s paper industry structural crisis) but failed to displace incumbents, producing mostly single innovations before ceasing commercialization. The five most prolific innovators, large pulp and paper manufacturers and external technology suppliers, remained active throughout both periods. However, the locus of bioeconomy innovation increasingly shifted beyond core forestry sectors during the product expansion period, driven by new firms that nevertheless built directly on existing forest-biomass processing knowledge, often mediated through academic networks. Third, bioeconomy innovations contradicted expert characterizations on every tested dimension. Logistic regression with period interactions (pre/post-1990) revealed that bioeconomy innovations were consistently associated with lower developmental complexity than other innovations and drew on narrower knowledge bases. Collaboration intensity showed no association before 1990 but became positively associated with bioeconomy innovation after 1990, providing partial and period-specific support for the bioeconomy literature's emphasis on cross-sectoral collaboration. Most strikingly, the association with public funding reversed entirely: positive before 1990, negative after 1990, the opposite pattern bioeconomy advocates predict.

2 Theoretical Framework—Extending Industry Life-Cycle Theory to Mature Industries

Peltoniemi (2011) organized 216 studies around the industry life cycle model and found that scholarship overwhelmingly concentrates on emergence and the transition to maturity; what happens after maturity received almost no theoretical treatment. Industry life cycle theory describes how industries emerge, grow, and mature, but is silent on what happens next. Swedish forestry reached maturity by the mid-20th century (Gaunitz, 1969; Gerard, 1958), yet it did not decline—it began producing novel bio-based products. Understanding this post-maturity dynamic requires extending the canonical ILC framework into territory it has not previously covered.

The economical use of biomass is not new (Vivien et al., 2019), and shifts in industry life cycles have characterized the global pulp and paper industry for the past 250 years (Ojala et al., 2012). Sweden's forestry sector shifted from technological laggard to leader in the latter part of the 20th century (Järvinen et al., 2012; Lehtinen et al., 2016; Lisberg Jensen, 2002). However, Ojala et al. (2012) predicted that the industry would eventually reach "the emergence of a totally different type of industry producing different products than today" (p. 360)—products spanning from fossil-fuel substitutes to novel pharmaceuticals, biotechnologies, and wood-based textiles (Losacker et al., 2023; Lovrić et al., 2020).

The ILC framework predicts what mature industries look like but offers no account of how they respond to such opportunities. Can the bioeconomy be seen as initiating a new industry life cycle for forestry? If so, is this new cycle competence-destroying or competence-enhancing—are there many new entrants, or is it driven by incumbents building on existing knowledge?

2.1 The Industry Life Cycle Model

The industry life cycle model provides a parsimonious framework to describe how industries evolve through phases of emergence, growth, maturity, and potential decline. These phases are characterized by systematic changes in price, quantity, and firm entry-exit dynamics, attributed to shifts in the quantity and quality of innovation (Gort and Klepper, 1982; Klepper and Graddy, 1990). Young industries are characterized by high innovation output, which decreases as the industry matures due to declining R&D intensity by incumbents. Simultaneously, the focus shifts from product to process innovations to ensure that inefficiencies—and thus costs—are reduced. At the same time, the supply of innovation changes from inside the industry to external actors. During emergence and growth, a diverse number of innovators rapidly enter and exit the industry, searching for superior technological solutions that allow firms to increase quality and reduce costs. After this turbulent phase, the industry matures and shifts to further reducing costs and increasing scales. While product innovations may not fully disappear, process innovations dominate the later industry life cycle phases; technological regimes direct search toward exploitation of scale economies and the mechanization of previously manual processes (Nelson and Winter, 1977). Incumbents can increasingly benefit from knowledge obtained through past experimentation, providing them an advantage over new entrants (Klepper, 1996). Consequently, the type of entry-exit dynamics can help identify what phase of the life cycle an industry occupies: rapid exits after entry for most innovators, with a few established and persistent large innovators, characterize mature industries, while the successful displacement of incumbents by new entrants may signify a more entrepreneurial regime during industry emergence or creative destruction (Audretsch, 1995). These observable patterns make the ILC framework empirically tractable, but they also expose its boundary: the model describes maturity well yet says nothing about what follows.

Canonical ILC theory is explicit about the maturity endpoint. Gort and Klepper (1982) excluded decline from their five-stage model because their data "generally do not extend to this stage" (p. 630); renewal received no theoretical treatment. Klepper (1997) acknowledged that "regular patterns occur when industries are mature that are not predicted by the product life cycle" (p. 145) and, in a footnote, directed readers to "a separate literature" (p. 149) for the displacement stage, which he did not review. The canonical model, in short, predicts what mature industries look like but is silent on what happens next. This paper works in that gap.

What might follow maturity depends on the character of any new technological opportunity. Tushman and Anderson (1986) distinguished between competence-destroying discontinuities, which render existing knowledge obsolete and favor new entrants, and competence-enhancing ones, which build on accumulated knowledge and reinforce incumbents. Their framework was developed within organizational ecology, not ILC theory, and is agnostic about cycle position: discontinuities can occur at any point in an industry's evolution. The explicitly cyclical model came from Anderson and Tushman (1990), who formalized a recurring sequence of technological discontinuity, era of ferment, dominant design emergence, and era of incremental change, after which a new discontinuity restarts the cycle. This is the closest any major framework comes to theorizing what happens after a period of incremental maturity, but it operates at the level of the technology rather than the industry population that is the ILC's unit of analysis. Whether a new technology cycle rejuvenates an existing industry or creates an entirely new one is a question the canonical ILC framework cannot answer.

These frameworks describe a general template. The template has received broad empirical support across different industries and locations, including Sweden (Bos et al., 2013) and core forestry industries (Ojala et al., 2012). However, Hayter and Edenhoffer (2016) argued that resource industries differ from the template due to additional influences from resource cycles. Since resource industries are centered on a primary raw material rather than a primary product, external suppliers of technology and process innovation play a larger role across different life cycle phases. Frequently, new processes give rise to new products, or allow existing products to be produced from inferior raw materials, further blurring the line between product and process innovations. Industry actors may develop some of these innovations in-house, but the reliance on external original equipment manufacturers tends to be stronger than in other industries. This mostly affects the maturity stage, which according to Hayter and Edenhoffer (2016) is reached when most or all of the available primary resource is exploited. Swedish forestry reached this stage at the latest in the middle of the 20th century (Gaunitz, 1969; Gerard, 1958). What theory offers for understanding what a mature resource industry does next is more scattered.

Post-maturity renewal has received scattered attention, but from adjacent literatures rather than within the ILC tradition itself. Bergek et al. (2013) showed that incumbents in mature auto and gas turbine industries could absorb competence-destroying discontinuities through "creative accumulation" rather than being displaced; Onufrey and Bergek (2021) documented a similar pattern in the Swedish pulp and paper industry specifically, finding that incumbents' innovation responses reflected deliberate strategic resource exploitation rather than lock-in. The sustainability transitions literature has engaged more extensively with mature industry transformation (for example, Geels and Turnheim, 2022; Köhler et al., 2019). Yet within the ILC tradition, the phenomenon remains under-theorized, particularly for resource industries where Hayter and Edenhoffer (2016) remains the only adaptation. Peltoniemi (2011) also noted that mature industries may enable the birth of technologically related new industries, but flagged this inter-industry effect as understudied—a prediction this paper's data allow me to revisit. Hansen (2016) drew precisely this conclusion from ILC logic, arguing that "the resulting culture and context of the industry does not place it well for transition to the bioeconomy" (p. 227). This paper tests that claim empirically, adopting the ILC framework because it generates directly testable predictions about innovation type, firm entry-exit, and the locus of innovation.

To summarize, the industry life cycle model predicts that a mature resource industry like Swedish forestry features mostly process innovations, produced by few, large internal actors and external technology suppliers. During the mature stage, new entrants are expected to be rare and generally fail to outcompete incumbents. This has been observed for the forestry industry at large (Ghosal and Nair-Reichert, 2009; Kubeczko et al., 2006; Ojala et al., 2012), as well as its core sectors in Sweden (Järvinen et al., 2012; Schön, 2014). The canonical model does not predict what follows maturity, but the theoretical scaffolding reviewed above provides expectations for what to look for. If the bioeconomy constitutes a new technological discontinuity in Anderson and Tushman's (1990) sense, it should re-initiate product innovation. Whether this discontinuity is competence-enhancing or competence-destroying determines who drives it: incumbents leveraging accumulated knowledge, or new entrants rendering that knowledge obsolete (Tushman and Anderson, 1986). Throughout, the role of external technology suppliers and process innovations should remain high, given the forest bioeconomy's dependence on a specific raw material (Hayter and Edenhoffer, 2016). The data and methods described next are designed to test these expectations.

2.2 Bioeconomy Innovation Literature: Drivers, Challenges, Expectations

What should be expected of bioeconomy innovation beyond "totally different products" (Ojala et al., 2012)? Although the bioeconomy concept is still highly contested, consensus exists around two core foundations (Bugge et al., 2016; Vivien et al., 2019). First, a bioeconomy ought to replace an economic system dependent on a finite and environmentally unsustainable fossil resource-base with a sustainable system built on renewable biomass (Allain et al., 2022). Second, substantial innovation is required to bring about such a transition, involving different actors, sectors, and broad knowledge bases (Patermann and Aguilar, 2021). Bröring et al. (2020) categorized bioeconomy innovation into four types (substitute products, new bio-based processes, new bio-based products, and new behaviors), noting that radically new products might favor startups, while large established companies may be better placed to develop substitutes for fossil bulk products. Building on Golembiewski et al. (2015), van Lancker et al. (2016) distilled five factors shaping bioeconomy innovation: radical and disruptive change across previously unrelated supply chains, complex knowledge bases spanning natural sciences, engineering, and ICT, intensive cross-sectoral cooperation (for similar arguments, see Rinaldi and Viaggi, 2025), high switching costs impeding commercialization, and fragmented policy schemes. The underlying claim is that bioeconomy innovation is qualitatively different from conventional innovation and demands a transdisciplinary approach.

These factors represent testable expectations about the nature of bioeconomy innovation. Specifically, the literature suggests bioeconomy innovations should be associated with: more radical product changes, greater knowledge complexity, more intensive collaboration, and higher public funding rates. I test these associations using logistic regression.

3 Data and Methods

Empirical research on bioeconomy innovation has relied primarily on patents and R&D expenditure, measures that have been criticized as insufficiently operationalizing industry life cycles due to varying propensities to patent between and within specific industries (Peltoniemi, 2011). Recent work by Kriesch and Losacker (2024) mapped the global bioeconomy innovation space using transformer-based patent classification, providing a comprehensive cross-sectoral view of technological knowledge. However, patents capture inventive activity, not commercialization—and the gap between the two is substantial (see Figure 1). Innovation output data can bridge this gap, as it remains an open question if the bioeconomy will materialize in the expected ways and entry-exit or price data for the bioeconomy is unavailable or difficult to collect correctly (Wydra, 2020).

3.1 Innovation Data

The main data of this paper stems from a database of commercialized Swedish innovation (Kander et al., 2019; Sjöö et al., 2014). Following the literature-based innovation output method (Kleinknecht and Reijnen, 1993), this continuously updated database contains 4972 innovations commercialized by Swedish companies between 1970 and 2021 discussed in 15 independent and edited trade journals

(Sjöö et al., 2014). These journals include specialized industry journals, (for example *Svensk trävaru- och pappermassetidning* [Swedish Wood Products and Pulp Magazine] published from 1970 to 1990, after which it became *Svensk Papperstidning* [Swedish Paper Magazine]), as well as general interest journals such as *Ny Teknik* [New Technology] and have been monitored consistently from the database's inception (Sjöö et al., 2014). Since these journals are independent, editors have a strong incentive to report timely, accurately, and comprehensively on topics of interest to their audience. Thus, covered innovations are likely to be significant, rather than mere product announcements or minor reconfigurations. In recent work, the innovations have been linked to applications to Swedish innovation agencies for public funding of innovation projects (Fink and Taalbi, 2024).

Since the database contains links to source articles, innovation biographies can be reconstructed—typically including technical specifications, intended applications, producing firms, development process, and market context—revealing qualitative shifts that aggregate statistics alone cannot capture.

3.1.1 Forestry Innovation

I defined the forestry sector as all innovations which were used or produced in the SNI divisions forestry and related services, wood and wood product manufacturing except furniture, pulp, paper and paper product manufacturing, and furniture manufacturing; other manufacturing. To ensure that furniture manufacturing innovations are restricted to wooden furniture only, I manually screened the innovations and excluded those that did not use any forest-sourced materials. In this way I identified 525 innovations belonging to the forestry sector in Sweden. These innovations underpin the industry life cycle analysis.

The classification follows product codes, not firm industry affiliation. A forwarder is classified under agricultural and forestry machinery (its product code), not under "forestry"; a pulp bleaching innovation falls under chemicals or paper machinery. What might colloquially be called "a forestry innovation" appears as a machinery innovation *used in* forestry, or a wood product innovation *produced in* wood manufacturing. The core sectors defined above (wood manufacturing, pulp and paper, furniture manufacturing) together with the user-sector variable jointly capture forestry innovation, and the produced/used distinction becomes central to the industry life cycle analysis in Section 4.2.

3.1.2 Defining Bioeconomy Innovation

However, the forest-based bioeconomy is a broader concept than innovations produced or used in central forestry sectors. It also includes novel products and processes produced from forest-derived raw material (Bröring et al., 2020; Wolfslehner et al., 2016). Based on previous literature, I developed a classification scheme to identify forest-based bioeconomy innovation in the database.

First, I used the core forestry sectors, saw-milling, and pulp and paper, and furniture manufacturing, as these represent the backbone of the forest bioeconomy. To account for the cross-sectoral nature of bioeconomy innovation, I combined this query with a keyword search of innovation descriptions. Keywords were related to forestry products, such as timber, wood, or its biological building blocks such

Table 1: Sectors and keywords used in bioeconomy innovation query

SNI Code – Sector	Keywords used in Swedish
02 – Forestry and related services 20 – Wood and wood product manufacturing except furniture 21 – Pulp, paper and paper product manufacturing 36 – Furniture manufacturing; other manufacturing	timber (virke); cellulose (cellulos); lignin (lignin); chip (spån); bark (bark); levulinic acid (levulinsyra); furfural (furfural); black tar (svarttjära); black liquor (svartlut); tallolja (tall oil); plant-based (växtbas); wood (ved); timber (trä); forest (skog); biofuel (biobränsle); biological (biologiskt); biodegradable (nedbrytbar); paper (papper); cardboard (pappret); carton (karton); lyocell (lyocell); Tencel (tencel)

as cellulose. A full list of all statistical sectors and all keywords are presented in Table 1, respectively. This way, an innovation such as a biofuel used in transport and originating in petrochemicals would still be covered if it were produced from wooden biomass. Since the keyword matching was performed on a substring level, I manually ensured that no false positives (for example, an algorithm using random forests) remained in the final dataset of forest bioeconomy innovation. To reduce the risk of false negatives, I manually reviewed innovations in adjacent sectors of high relevance to the bioeconomy, such as organic chemicals, plastics, or construction. This identified three missed keywords, which I then added to the query. Applying this new search yielded three additional innovations, indicating that the approach was already highly accurate.

This approach has three key features worth noting. First, it captures both core forestry sectors and cross-sectoral applications, addressing concerns about the bioeconomy's transdisciplinary nature, while keeping the industry life cycle analysis consistently focused on industrial boundaries. Second, capturing actual innovation ensures that sectoral differences in R&D intensity, or patent propensity (see Figure 1), do not bias comparisons across sectors. Third, using a trade journal based innovation output measure ensures that only successful innovations are included—failed or pre-commercial efforts are not observed. As long as the reporting standards and trade journals remain consistent across the Swedish innovation system, this limitation applies equally to bioeconomy and non-bioeconomy innovations. As there is no evidence that suggests such changes, there should be no such bias in the comparisons.

3.2 Analyses

I examined bioeconomy innovation patterns from three complementary perspectives. An exploratory data analysis exposes long-term trends and patterns in bioeconomy innovation output. In addition to the graphical analysis of output statistics, this includes qualitative analysis of innovation trends based on the innovation biographies underpinning the database. Third, I modeled the probability of an innovation being a bioeconomy innovation using logistic regression. The model incorporates

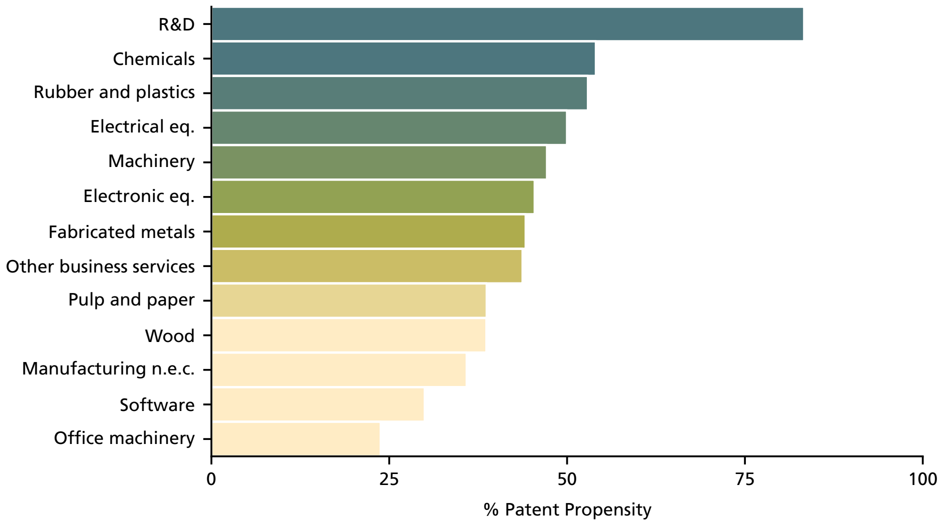

Figure 1: **Patent Propensity of Bioeconomy Innovations by Sector.** Calculations based on Johansson et al. (2022) and Taalbi (2025).

developmental complexity, number of collaborating partners, producer characteristics, and public funding status.

A second analytical perspective examines the locus of innovation by distinguishing innovations *produced* within core forestry sectors from innovations *used* in those sectors. This distinction has a long lineage: Pavitt (1984) classified resource-processing sectors as supplier-dominated, receiving process innovations from specialized machinery and instrument producers rather than generating them internally, and Taalbi (2017) confirmed this for Swedish forestry using the same SWINNO database, finding that forestry and pulp and paper were overwhelmingly user sectors. This supplier-dominated position is precisely what Hayter and Edenhoffer (2016) predict for mature resource industries. The produced/used distinction therefore provides a direct test of whether the post-1990 period departed from this structural baseline.

3.3 Innovation Level Analysis

To explore the associations between characteristics of bioeconomy innovation proposed in the literature, I employed logit regression models. The general specification is:

$$\text{logit}(P(\text{bioeconomy}_i = 1)) = \alpha + \mathbf{X}_i\beta + (\mathbf{X}_i \times \mathbb{1}\{t > 1990\})\gamma + \mathbf{Z}_i\delta \qquad (1)$$

where i indexes individual innovations and t denotes the year of commercialization. X_i denotes the main predictors, $\mathbb{1}\{t > 1990\}$ is a binary indicator equal to one if the innovation was commercialized after 1990, and their product $\mathbf{X}_i \times \mathbb{1}\{t > 1990\}$ yields a vector of interaction terms that allow coefficients to differ across the two periods. $\mathbf{Z}_i$ denotes commodity price controls. The key explanatory factors in $\mathbf{X}_i$ are:

- Developmental complexity (Low, Medium, High): disciplinary scope of the innovation.
- Number of collaborators: count of distinct actors involved in commercialization.
- Public funding: binary indicator of whether the innovation received public funding.
- Knowledge base: cumulative count of distinct industrial sectors from which collaborating actors drew prior innovations.

Each of these variables is described in more detail in the following subsection.

The model compares bioeconomy innovations against all non-bioeconomy innovations in the database. The bioeconomy literature makes unconditional claims—bioeconomy innovation is more complex, requires broader collaboration, and so on—without specifying a comparison sector. The natural test of an unconditional claim is against the full population of commercialized innovations. The comparison pool is heterogeneous, so coefficients reflect an average contrast, but restricting the comparison to a single sector would introduce more arbitrary assumptions than it resolves.

I included all of these main effects interacted with a binary indicator for commercialization after 1990 to test whether associations between predictors and bioeconomy innovation differed across the two periods identified in the descriptive analysis. I chose 1990 as the breakpoint based on qualitative patterns in the innovation database and prior work by Taalbi (2021) and Schön (2014) that identified structural transitions in Swedish industry cycles around this year. The interactions allow the coefficients γ to capture period-specific effects, testing the hypothesis that bioeconomy innovation characteristics changed as the sector transitioned from rationalization to diversification.

The vector $\mathbf{Z}_i$ includes controls for path-dependency and commodity prices. I measured path dependency as the log-odds of bioeconomy innovation shares in the previous year, $\log(S_{t-1}/(1-S_{t-1}))$. Price controls include 5-year moving averages and first-differences of international crude oil prices (real 2010 USD/barrel) and Swedish gross stumpage values (2023 SEK/m^3). Moving averages capture medium-run strategic responses to market trends, while first-differences capture responses to short-term price shocks. I clustered standard errors by firm to account for repeated innovations within firms.

3.3.1 Independent Logit Variables

The construction of developmental complexity and knowledge base requires more detailed description.

Developmental Complexity

The database contains information about the developmental complexity behind an innovation. The variable distinguishes three levels: Low, Medium, and High. Low denotes a single discipline being involved, Medium two, and High more than two disciplines. This variable is coded based on information in the source article.

Knowledge Base

I derived a complementary perspective of complexity through the knowledge base an innovation drew on. To measure the knowledge base of an innovating actor, I used data on previous commercialized innovations. Each observed innovation in the database possesses a code indicating the economic sector in which it originated. These codes follow the 2002 version of the Swedish Standard Industrial Classification (SNI) (Statistics Sweden, 2004). These codes mostly consist of multiple digits, becoming increasingly detailed at each digit. For example, the manufacture of paper and paper products is classified with code 21, its children include: manufacture of pulp, paper and paperboard (211), manufacture of pulp (2111) and finally, manufacture of mechanical or semi-chemical pulp (21111).

First, I cumulated the product codes of all previous registered innovations for each actor. Since this approach only provides information after the first innovation, I supplemented the data with SNI codes registered in Sweden's business registry. These codes were homogenized to 2002 standards using a manual process described in detail in Kreutzer and Taalbi (2026). I then merged these registry codes with the product codes, lagging them in time so that a firm's knowledge at time of the first innovation corresponds to their registered SNI code and all subsequent innovation output for all following innovations.

In counting the knowledge base, I restricted the codes to the first two digits, corresponding to the taxonomy's division. For a given innovation, the knowledge base was defined as the cumulative set of previous product codes (including from registry data) from all collaborating actors involved in that innovation at time $t - 1$.

3.3.2 Commodity Prices

Prices influence the direction of innovation (for example, Popp, 2006). Two prices which are likely to matter for bioeconomy innovation are wood and oil prices. Higher wood prices could make it more attractive to produce innovation which further increases value added of biomass usage. Changes in oil prices could create incentives to produce substitute products.

Data on oil prices were retrieved from annual commodity prices published by the World Bank and represent average crude oil prices (real 2010 USD / bbl) (World Bank Group, 2025). Swedish wood prices are measured as gross stumpage value per m^3, representing the economic value of felled timber before subtracting all costs in 2023 SEK (Swedish Forest Agency, 2023).

3.3.3 Missing Values

For innovations where no collaborating actors were recorded in the source article, I coded the number of collaborators as zero. The trade journals named collaborating partners when present but did not explicitly state their absence; silence most likely indicates sole commercialization. This affected 631 observations.

After this imputation, the logit estimation sample comprises 4,183 of the 4,972 innovations in the dataset. The remaining 789 observations were dropped due to missing values, primarily on Knowledge

(631 observations). Bioeconomy innovations constituted 13.1% of the full SWINNO dataset and 13.1% of the logit estimation sample, indicating that attrition did not disproportionately affect the comparison of interest. A summary of missing values by variable can be found in Table A1.

4 Results

This section first establishes a periodization of forest bioeconomy innovation through descriptive evidence, then examines industry dynamics through the ILC lens, and concludes with an innovation-level analysis of the characteristics commonly attributed to bioeconomy innovations.

4.1 Two Eras of Forest Bioeconomy Innovation

Figure 2 shows the trends of innovation commercialized in total (a), in the bioeconomy (b), and the relative share of bioeconomy to total innovation (c) between 1970 and 2021. Panel b shows that the number of annual bioeconomy innovations first rose and then declined in the period of 1970 to 1990, remained relatively stable until 2015 and then declined again. On average, 12.48 (SD=5.36) innovations were commercialized each year with a total of 649 forest-based bioeconomy innovations.

The share of bioeconomy innovation relative to all innovations in the database (panel c) declined from a high of 27% in 1976 to 11% in 2021 (with an absolute minimum of 3% in 2002). This decline reflects not a collapse in bioeconomy innovation output, but rather Sweden's broader innovation surge after 1990 (panel a), which reached a second peak in the late 2000s. Previous work has attributed this surge to an expansion of ICT innovations in the late 1990s (Kander et al., 2019). Although ICT plays an increasing role for bioeconomy innovation after 1990, the bioeconomy's second output surge was less pronounced than the overall pattern, suggesting sector-specific dynamics rather than a general ICT-led expansion.

Closer examination of the innovation biographies reveals that this aggregate stability masks fundamental qualitative changes in the nature and direction of bioeconomy innovation. The period divides into two distinct eras separated by a structural break around 1990. From 1970 to 1990, bioeconomy innovation mostly optimized modular components and aimed at improving the efficiency of existing processes. The oil crises provided some stimulus to attempt product diversification, but these innovations failed to catch on after price pressures decreased again. In contrast, after 1990, innovations frequently encompassed integrated systems often supported by or mostly based on software. The aim of these innovations also broadened: efficiency and process optimization remained a constant feature, but additionally innovations aimed to upgrade wooden biomass into novel products.

The aggregate stability also masks a compositional shift that complicates a simple incumbent-driven narrative. Figure 3 decomposes the bioeconomy sample by sectoral boundaries: innovations produced or used in core forestry sectors versus those in other sectors—such as chemicals, construction, and energy—that nevertheless use forest-derived biomass.

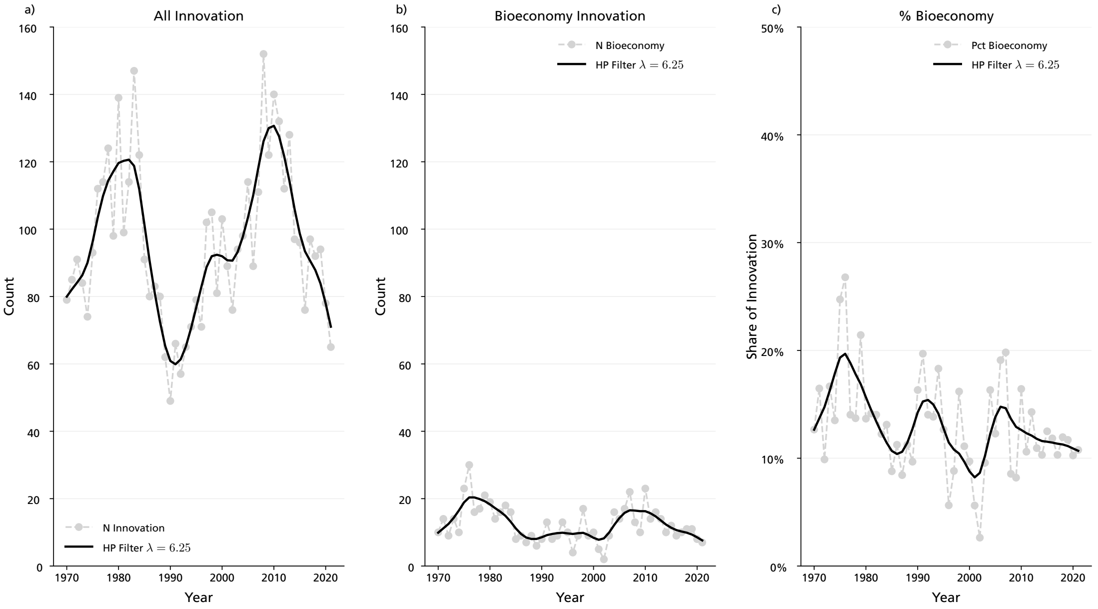

Figure 2: **Annual Innovation Output** Panel a) displays innovation counts of all innovations in the SWINNO database; panel b) bioeconomy counts; panel c) displays the annual share of bioeconomy innovation. Solid lines are smoothed count statistics using HP filtering with $\lambda = 6.25$, grey dots display raw counts.

Before 1990, bioeconomy innovation was overwhelmingly a core-sector phenomenon, with outside-core innovations accounting for roughly 10 to 25% of the total. After 1990, this share rose substantially, reaching 40 to 50% in recent years. The product expansion period did not only change what the forestry sector innovated; it changed where forest biomass knowledge was applied.

Who produced these outside-core innovations matters for interpreting the industry life cycle dynamics examined in Section 4.2. If incumbents diversified into adjacent sectors, the transition would remain competence-enhancing at the firm level even as it crossed industrial boundaries. The non-core innovations suggest a more nuanced pattern. Several innovations after 2010 were produced by new entrants specializing in biomass valorization: Re:NewCell, a cellulose textile recycler (Taalbi et al., 2025, no. 11546001), Cellutech, a cellulose-based foam producer (Taalbi et al., 2025, no. 13890001), RenCom, a lignin bioplastic developer (Taalbi et al., 2025, no. 12322001), and Ligna Energy, a lignin-based battery producer (Taalbi et al., 2025, no. 14003001), among others. However, the rising share of innovations outside core sectors in Figure 3 b) should be interpreted cautiously. The increase coincides with a decline in core-sector innovation output visible in Figure 3 a), which could reflect incumbents shifting resources from commercializing new innovations toward scaling and diffusing products developed during the preceding output surge. A compositional shift in the ratio does not necessarily indicate a surge of outside-core activity.

This pattern complicates a simple competence-enhancing interpretation, but it does not amount to creative destruction. The new entrants built on knowledge developed within forestry, particularly cellulose and lignin chemistry refined over decades in pulp and paper processing. Several, including Re:NewCell and Cellutech, emerged from collaboration with KTH, suggesting the knowledge traveled through academic networks rather than through incumbent diversification directly. Within core forestry sectors, established firms continued to dominate innovation output throughout the period, as shown in the following sections. The growing outside-core share may represent an instance of the inter-industry effect Peltoniemi (2011) predicted: mature industries enabling the birth of technologically related new ones. The industry life cycle analysis in Section 4.2 therefore focuses on core-sector dynamics, where incumbent persistence is most clearly observed, and I return to the outside-core pattern in the conclusion.

The aggregate statistics establish a structural break around 1990, but they cannot reveal what changed in the *character* of innovations. The following subsections draw on innovation biographies from the SWINNO source articles to illustrate the qualitative shift from modular component optimization to integrated systems and novel products.

4.1.1 Component Optimization (1970–1989)

Prototypical innovations of the component optimization period between 1970 and 1990 were Kockum's silvicultural machines discussed in *Sågverken* (1974:10, pp.725–727). A mechanical feller and forwarder, which "at a superficial examination … may be regarded as conventionally constructed" (my translation), allowed to fully mechanize the felling work. The efficiency of forest operations was a central consideration for these innovations, as illustrated by another forwarder's biography which reported that, "… today, the need for thinning is great, and [the forwarder] has been directly adapted to this situation" (*Sågverken*, 1975:10, p. 731, own translation). Or, as summarized by a new program

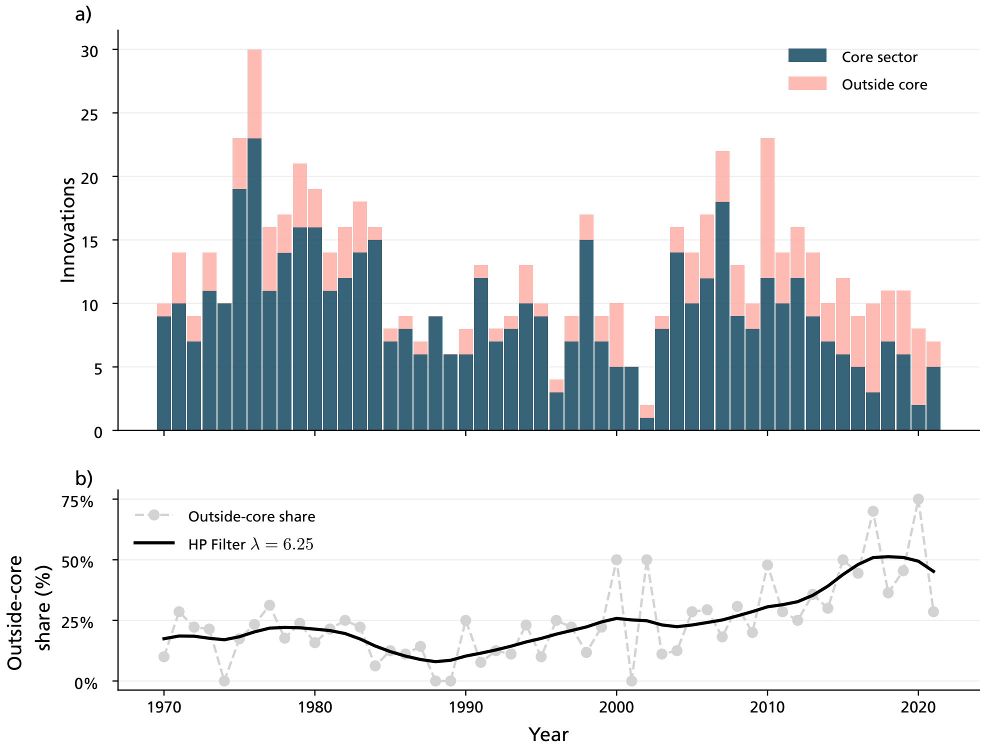

Figure 3: **Bioeconomy Innovation by Classification Mechanism.** Panel a) distinguishes innovations produced or used in core forestry sectors and those produced or used in other sectors. Panel b) displays the outside-core share over time, smoothed with an HP filter ($\lambda = 6.25$). Core sectors include forestry, wood manufacturing, pulp and paper, and wooden furniture manufacturing.

of connected harvesting machines commercialized by ÖSA in 1975, it was important to "… meet demands of forestry for full mechanization …", "… from stump to harvest …", in a manner which "… suits existing methods and conditions [and] is most economical" (*Sågverken*, 1975:12, p. 905, own translation).

Efficiency and process optimization were not only a concern in the forests, downstream processing innovations were similarly directed toward these goals. An example of this effort is a new method to produce wood chips reported on in edition 11 of 1975's *Sågverken*: its specifications demanded high quality wood chips to be produced from roundwood, stumps, and root-bone twigs alike while being able to "apply the new technology directly to existing chipping machines", ultimately to "increase the profitability of woodchip production by significantly reducing waste" (p. 839, own translation).

Despite this efficiency focus, the period also seeded novel products. Expectations were high, for example, when the introduction of modal fibers in Sweden generated an article in *Ny Teknik*, 1976:9 (pp. 4), titled "Wood Replaces Cotton". However, such truly novel products were the exception. Product innovations usually focused on meeting market demands such as a new paper commercialized in 1977 which could be used in a multitude of use cases across different printing techniques following the strong machine development of the 1970s and 1980s (*SPCI Svensk Papperstidning*, 2004:8: pp. 34–37).

In summary, the period from 1970 to 1989 saw forestry innovation mostly respond to the demands and pressures of a highly competitive resource industry. Major players focused on producing technologies which could seamlessly fit into existing processes in order to decrease costs and increase efficiency. The majority of these innovations were mechanical, and modular in nature, but did not fundamentally alter what Swedish forestry industries produced or which markets they served. At the same time, seeds of the product expansion period can already be identified in the period 1970 to 1990: rare novel products outside the traditional applications of wooden biomass, integrating machines in connected platforms, and increasingly computerization.

4.1.2 Product Expansion (1990–2021)

Around 1990, Swedish forest bioeconomy innovation entered a new phase. The number of bioeconomy innovations had followed overall innovation output patterns, rising to an all-time high in the 1970s, declining during the 1980s and stabilizing at a moderate level during the 1990s. With the new millennium, innovation output increased again, although it failed to reach previous highs. After 1990, the type of innovations produced shifted toward fully integrated systems and new products for new markets. This shift coincides with the emergence of a strong policy discourse around the "bioeconomy" (Pülzl et al., 2014).

New products were introduced from both major forestry pillars. Sawn timber was increasingly commercialized in ambitious construction systems, such as a wooden beam which was praised for its light weight and insulating properties (*Ny Teknik*, 1997:9, pp. 24–25); or a wooden frame-based construction method to build multi-story buildings in factories before assembling them onsite, establishing wood as an alternative to steel and concrete (*NTT*, 2004:18, pp. 16–17). Other new products remained curiosities rather than commercial successes, such as an electronic card made of wood described in *Nordisk Träteknik* (1996:2 p. 5), but serve to illustrate the effort to develop entirely novel products and drastically expand the usage of wooden biomass.

Even more drastic were efforts in the pulp and paper sector. Already during the previous decades pulp mills shifted from energy consumers to producers, utilizing waste and byproducts to generate heat and electricity (Bergquist and Söderholm, 2015, 2016; Ottosson and Magnusson, 2013). However, after 1990 these efforts intensified and their scope expanded. One of the most salient examples is a large commercial pilot plant for biorefined tall oil which began operations as a joint venture between forest owners, an oil company and pulp and paper producers in Piteå in 2010 (*Ny Teknik*, 2010:18, p. 10). Biofuels were not the only new product line; pulp and paper actors also extended their knowledge of cellulose fibers to creating (re-cycled) textiles (*Kemivärlden Biotech med Kemisk Tidskrift*, 2012:11, p. 34), or to replace plastics with biodegradable alternatives (for example Södra's DuraPulp covered in *Plastforum*, 2011:6, p. 8; or Cellutech's Cellufoam discussed in *Ny Teknik ; Automation*, 2013:41(6), p. 19).

Traditional process innovation to increase efficiencies remained a feature of this period, as can be seen in continued forwarder innovations along established trajectories of reduced weight, higher fuel efficiency and increased capacity (*Ny Teknik Automation*, 2012:40, p. 26). Increasingly, however, these innovations comprised large, connected systems such as a combination of cameras and software to analyze and measure pulp and paper flows (*Automation*, 2012:2, pp. 18–21).

In short, from 1990 to 2021 the forestry sector experimented with new products, found new markets, and forged new alliances. Yet the quality of these innovations suggests that the expansion built on decades of accumulated experience. The shift from externally supplied process innovations to internally produced novel products marks a departure from the supplier-dominated pattern that had defined Swedish forestry for decades—a shift visible in the produced/used analysis that follows.

4.2 Industry Life Cycle

Having established the two periods of forest bioeconomy innovation and overall output pattern, I now turn to examine if these patterns conform to the industry life cycle theory. For this, I rely on the narrower core-sector definition of innovation in the following section. By and large, the results show that the sector was in line with expectations of a mature industry before 1990, and that the product expansion period is a competence-enhancing rejuvenation driven by incumbent actors.

4.2.1 Innovation Production and Usage Patterns

Industry life cycle theory predicts that mature resource industries rely heavily on external suppliers for process innovations, while producing few innovations themselves (Hayter and Edenhoffer, 2016). Figure 4 tests this prediction by distinguishing innovations produced within core forestry sectors (forestry and related services, wood and wood product manufacturing except furniture, pulp, paper and paper product manufacturing, and wooden furniture manufacturing) from innovations used in these sectors.

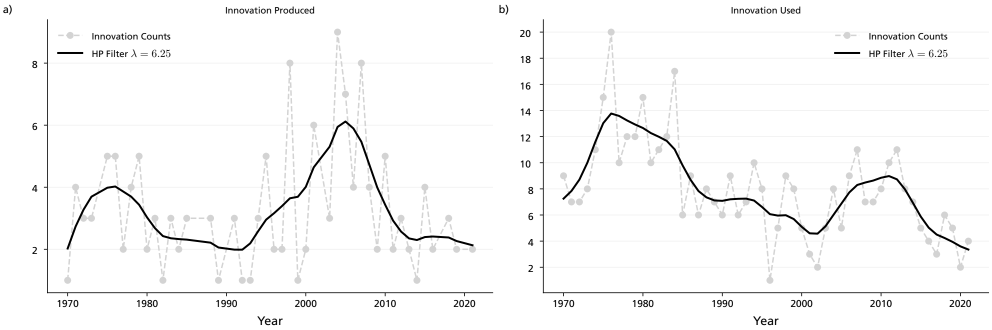

Figure 4: **Annual Innovation Output Produced And Used In Core Forestry Sectors.** Panel a) shows innovations produced within core sectors and panel b) innovations used in core sectors. Core sectors include Forestry, Wood Manufacturing, Pulp and Paper, Wooden Furniture Manufacturing. Note: y-axes differ between panels and are not directly comparable.

The component optimization period (1970–1990) fits expectations of mature resource industries: innovation use (panel b) substantially exceeded innovations produced in the sectors (panel a), peaking at 20 used innovations compared to 5 produced innovations. This persistent dominance of use over production is consistent with the supplier-dominated position Taalbi (2017) documented for Swedish forestry and that Hayter and Edenhoffer (2016) predict for mature resource industries. The gap indicates a strong dependence on external suppliers of technology, who provided the mechanization and process control technologies to improve the harvesting and processing of wooden biomass into established sawn timber and paper products. Innovations in this period were largely modular and improved existing processes. In the product expansion period following 1990, a reversal of this pattern can be observed. While the industry still heavily relied on externally produced innovations, innovations produced within it steadily increased from 1990 onwards. At their peak around 2010, the forestry sector produced almost as many innovations annually as it used. This shift toward production parity represents a departure from the established supplier-dominated position that had characterized Swedish forestry for decades.

This transition from technology adopter to technology producer represents a fundamental shift in the locus of innovation. Increasingly, the sector focused efforts on producing novel wood-based products, primarily drawing on existing knowledge around materials and processes. Examples include refined biofuels from lignin, and cross-laminated timber products for construction.

Process improvements remained important. But rather than the modular improvements through individual machines or tools during the component optimization period, innovations were more systematic after 1990. Usually this entailed drawing on software and specialized equipment to integrate production processes, examples include systems for harvesters, and pulp and paper flow control.

While the data before 1990 fit mature resource industry life cycle dynamics identified by Hayter and Edenhoffer (2016), the product expansion period does not. Instead, since 1990, Swedish forestry firms have responded to new technological opportunities and begun seeking to expand their capabilities in pursuit of novel products. These patterns are consistent with a competence-enhancing discontinuity that has re-initiated product innovation within a mature industry without displacing incumbents, the post-maturity dynamic that canonical ILC theory leaves undertheorized.

4.2.2 Firm Innovation Output Dynamics

A second core component of industry life cycle phases is firm entry and exit behavior. To stay consistent with my focus on technological change, I focus on the innovation output of firms rather than examining firm population dynamics. I define an entry into the innovation system as the firm's first commercialized innovation produced or used in core forestry sectors. Firms remain active until their last recorded innovation, which I here treat as the firm exiting the innovation system. Although this approach may slightly undercount active firms—as first-time innovators could potentially produce subsequent innovations beyond the observation period—the overwhelming majority of firms produced only one innovation, making this concern minimal. Additionally, the average duration between subsequent forestry innovations was 6.4 years (median 4.0 years, maximum 29 years), indicating that most firms either exited immediately or had very long gaps between innovations.

Figure 5 displays three different perspectives on firm's innovation output. Panel a) shows that the majority of firms active in the forestry sector were one-time innovators, while the most prolific innovators produced no more than 10 innovations in 52 years. This highly right-skewed distribution shows that new innovators struggled to gain a foothold in the industry, and the few firms that could produce subsequent innovations did so rarely.

Panel b) examines the five most innovative firms more closely, plotting the years in which they commercialized innovations against their cumulative innovation counts. Several patterns emerge from this panel. First, all five leading innovators remained active throughout the entire study period, demonstrating remarkable persistence. Second, these firms include both large pulp and paper manufacturers and major external technology suppliers, collectively forming the backbone of the forestry innovation system. Third, their continuous presence across both component optimization and product expansion periods reveals that they successfully adapted to the changing innovation regime. The stability of this leading group—with no displacement by new entrants despite the qualitative shift toward product expansion—indicates that the bioeconomy transition built on rather than destroyed existing competences. Established forest sector firms leveraged accumulated knowledge of biomass processing, supply chains, and market relationships to navigate the shift from discrete component improvements to integrated systems.

Panel c) reinforces this picture of incumbent persistence alongside modest entrepreneurial activity. It reveals that the 1970s and 2000s were particularly entrepreneurial decades in forestry innovation, with surges in new entrants commercializing innovations. However, most of these entrants failed to establish persistent innovation activities, producing single innovations before exiting. The 1970s surge coincided with the oil crises, which temporarily stimulated experimentation with biomass-based energy alternatives and process efficiency improvements. The 2000s surge occurred amid a structural crisis affecting the forestry sector, particularly pulp and paper, as demand for printing paper declined due to ICT adoption, forcing strategic reorientation (Schön, 2014).

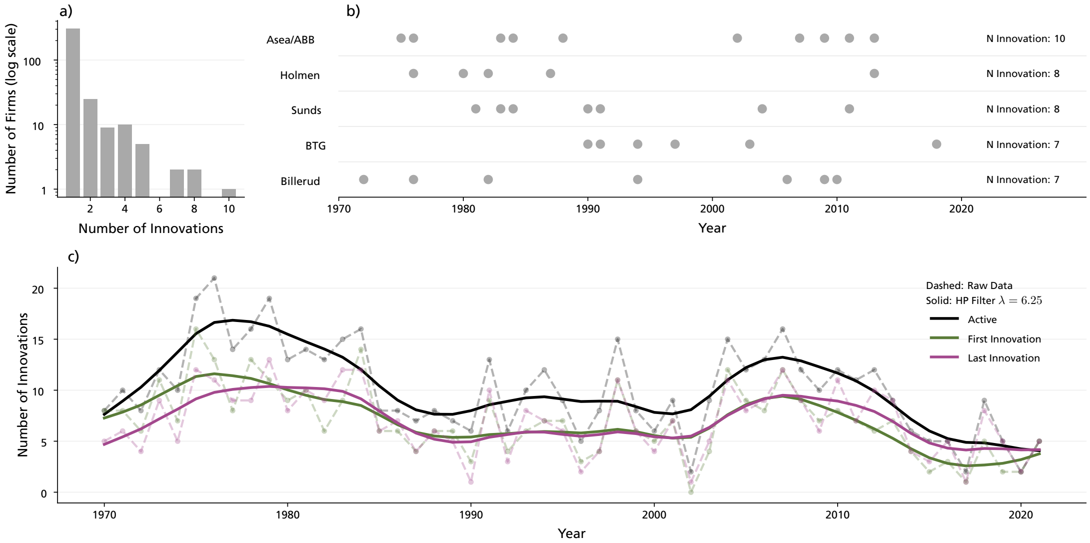

Figure 5: **Innovation Output Dynamics of Innovating Firms Within Core Forestry Sectors.** Panel a) shows the distribution of commercialized innovations used or produced in core forestry sectors by firms; panel b) shows the timing of innovations used or produced in core forestry sectors for the 5 largest innovators; panel c) displays the number of innovating firms per year, defined as having produced an innovation that year. Entries are firms innovating for the first time. Exits are the last recorded innovation. Core sectors include Forestry, Wood Manufacturing, Pulp and Paper, Wooden Furniture Manufacturing.

This pattern—entrepreneurial entry during crisis periods combined with persistent dominance by established innovators—suggests a competence-enhancing rather than competence-destroying transition. New entrants contributed specialized innovations, often as suppliers or in niche applications, but did not displace incumbents. Instead, established forest sector firms responded to strategic challenges by leveraging existing knowledge of biomass processing, supply chains, and markets to develop new products, integrate production into comprehensive systems, and improve operational efficiency and environmental performance. Onufrey and Bergek (2021) reached a complementary conclusion from a firm strategy perspective, showing that Swedish pulp and paper companies' innovation responses to bioeconomy transformation pressures reflected deliberate matching of new market opportunities to existing resource bases rather than path dependency or inertia. The innovation output data presented here corroborate that finding from the opposite direction: the pattern visible in firms' strategic choices is also evident in their actual innovation output. To assess whether this pattern of incumbent persistence and entrepreneurial entry reflects a forestry-specific dynamic rather than a broader trend in Swedish manufacturing, the following section compares forestry's output patterns with two other mature industries.

4.2.3 Comparative Perspectives: Forestry, Metals, and Automotive

To assess whether the shift toward production parity was specific to forestry or part of a broader Swedish trend, I compared forestry's output patterns with two other mature industries: metal manufacturing and motor vehicles (Figure 6 and Figure 7).

The automotive industry displayed a completely different pattern, with no comparable shift toward production parity, ruling out a generic Swedish trend. Metal manufacturing *resembled* forestry's shift toward production orientation after 1990, but with a critical difference: metals' post-1990 increase represented a *return* to innovation output levels from the 1970s and 1980s—a cyclical recovery, not a structural discontinuity. This is visible in the broader innovation surge documented in Figure 2, which metal manufacturing participated in alongside much of Swedish industry. Forestry, by contrast, reached production levels it had never previously achieved. This distinction—return versus discontinuity—is what separates life cycle rejuvenation from cyclical fluctuation and supports the claim that the post-1990 shift in forestry represents a qualitatively new phase.

4.3 Bioeconomy Innovation Characteristics—An Innovation Level Perspective

The descriptive analysis established that Swedish forestry underwent a qualitative transformation around 1990, with innovation shifting from external suppliers improving existing processes to incumbents developing novel products. I now test whether bioeconomy innovations exhibited the characteristics commonly attributed to them: greater complexity, broader knowledge requirements, more intensive collaboration, and higher dependence on public funding.

Table 2 presents average marginal effects from logit regression predicting the probability that an innovation was a forest-based bioeconomy innovation. The model includes interactions with a post-1990 indicator to test whether associations changed across the two periods identified in the descriptive

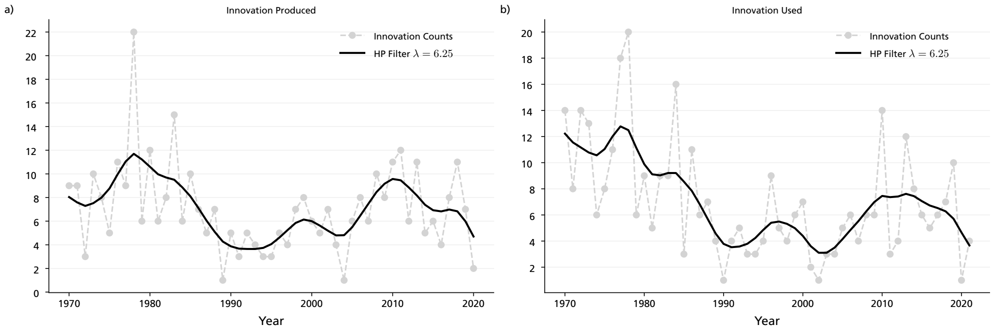

Figure 6: **Annual Innovation Output Produced And Used In Metal Manufacturing Sectors.** Panel a) shows innovations produced within core sectors and panel b) innovations used in core sectors. Metal sectors include manufacture of basic metals and fabricated metal products, except machinery and equipment. Note: y-axes differ between panels and are not directly comparable.

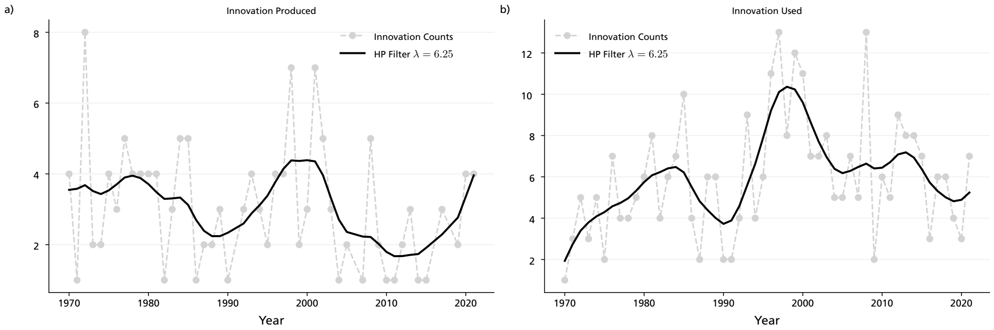

Figure 7: **Annual Innovation Output Produced And Used In Motor Vehicles, Trailers and Semi-Trailers Manufacturing Sectors.** Panel a) shows innovations produced within core sectors and panel b) innovations used in core sectors. Note: y-axes differ between panels and are not directly comparable.

analysis. Figure 8 visualizes these relationships as predicted probabilities, holding other variables at representative values (means for continuous and modes for categorical covariates).

Contrary to expectations, bioeconomy innovations were consistently associated with lower complexity (Figure 8 a). Low complexity innovations showed roughly 20% probability of being a bioeconomy innovation in both periods. As complexity increased to medium and high, the probability of an innovation being a bioeconomy innovation declined to roughly 12% and 6%, respectively. The near complete overlap between component optimization (purple) and product expansion (green) periods indicates the stability of this negative relationship across the two periods. This pattern directly contradicts claims that bioeconomy innovation requires more complex, multidisciplinary development efforts.

The association between knowledge bases and innovation outcomes (Figure 8 b) corroborates this point. Innovations drawing on broader pre-existing knowledge were less likely to be a bioeconomy innovation. However, this relationship weakened substantially after 1990. At low knowledge diversity (around 4 distinct SNI codes, close to the mean), predicted probabilities remained similar, around 13%. At the highest observed diversity (22 SNI codes), the gap widened: pre-1990 probability dropped to 4%, while post-1990 remained around 7%. The steeper pre-1990 slope (purple line) compared to the flatter post-1990 slope (green line) shows that knowledge diversity became less penalizing for bioeconomy innovation, though it remained negatively associated.

Figure 8 c) reveals a period-specific pattern for collaboration. The pre-1990 line (purple) is essentially flat around 13% across all collaboration intensities, indicating no association between the number of collaborators and bioeconomy innovation during the component optimization period. After 1990, however, the relationship turned positive: each additional collaborator increased the predicted probability of bioeconomy innovation by approximately 2.9 percentage points (see Table 2). This shift provides partial support for the bioeconomy literature's emphasis on collaboration, but only during the product expansion period when incumbents began developing novel products rather than optimizing existing processes. The absence of any collaboration effect before 1990 suggests that cross-sectoral partnerships became relevant specifically as innovation moved beyond modular component improvements toward integrated systems and new bio-based products.

One of the most striking findings is the reversal in public funding's association with bioeconomy innovation (Figure 8 d). Before 1990, innovations that received public funding had a roughly 15% predicted probability compared to roughly 10% for unfunded innovations. However, during the product expansion phase—when bioeconomy innovations are argued to require more public support—the pattern reversed: having received funding was associated with an approximately 12% probability of being a bioeconomy innovation, compared to about 15% for unfunded innovations. Whether this reversal was driven by a decline in bioeconomy innovators seeking funding, or a shift in funding agencies' decision-making cannot be discerned with this data, but represents an important avenue for future research. This result does show, however, that bioeconomy innovations have received less public funding after 1990.

In summary, the majority of claims regarding bioeconomy innovation characteristics cannot be substantiated by empirical evidence. On the contrary, core arguments—such as requiring higher complexity or broader knowledge bases—were directly contradicted: bioeconomy innovations were consistently less complex and drew on narrower knowledge bases than other commercialized innovations.

Table 2: Average Marginal Effects of Logit Regression on P(Bioeconomy Innovation | Innovation)

Variable	Primary
Medium Dev. Complexity	-0.074*** (0.022)
High Dev. Complexity	-0.115*** (0.018)
Medium Dev. Complexity × Post-1990	-0.004 (0.026)
High Dev. Complexity × Post-1990	0.018 (0.047)
Knowledge	-0.009*** (0.002)
Knowledge × Post-1990	0.005* (0.003)
N Collaborators	0.001 (0.012)
N Collaborators × Post-1990	0.029** (0.014)
Public Funding	0.052** (0.023)
Public Funding × Post-1990	-0.063*** (0.019)
Post-1990	0.025 (0.028)
Price Controls	Yes
Path Dep. Control	Yes
N	4183

*p<0.1; **p<0.05; ***p<0.01
Standard errors clustered by commercializing firm in parentheses.

5 Conclusion

This paper examined 649 forest-based bioeconomy innovations commercialized in Sweden between 1970 and 2021 to test central claims about bioeconomy innovation and understand how a mature resource sector adapted to new technological opportunities. Three main findings emerge.

First, Swedish forestry underwent a structural transformation around 1990, shifting from optimizing individual components to expanding its product portfolio. The component optimization period (1970–1989) focused on mechanizing existing processes through modular improvements supplied by external technology providers. The product expansion period (1990–2021) saw incumbent firms increasingly develop integrated systems and novel bio-based products, from construction materials to biofuels to textile fibers. After 1990, core forestry sectors shifted from predominantly adopting externally-developed technologies to producing innovations themselves.

Second, this transition extends industry life-cycle theory into territory it has not previously covered. The bioeconomy represents competence-enhancing rejuvenation rather than competence-destroying disruption, a post-maturity dynamic the canonical ILC framework acknowledges but does not theorize. Established incumbents maintained dominance throughout both periods, successfully

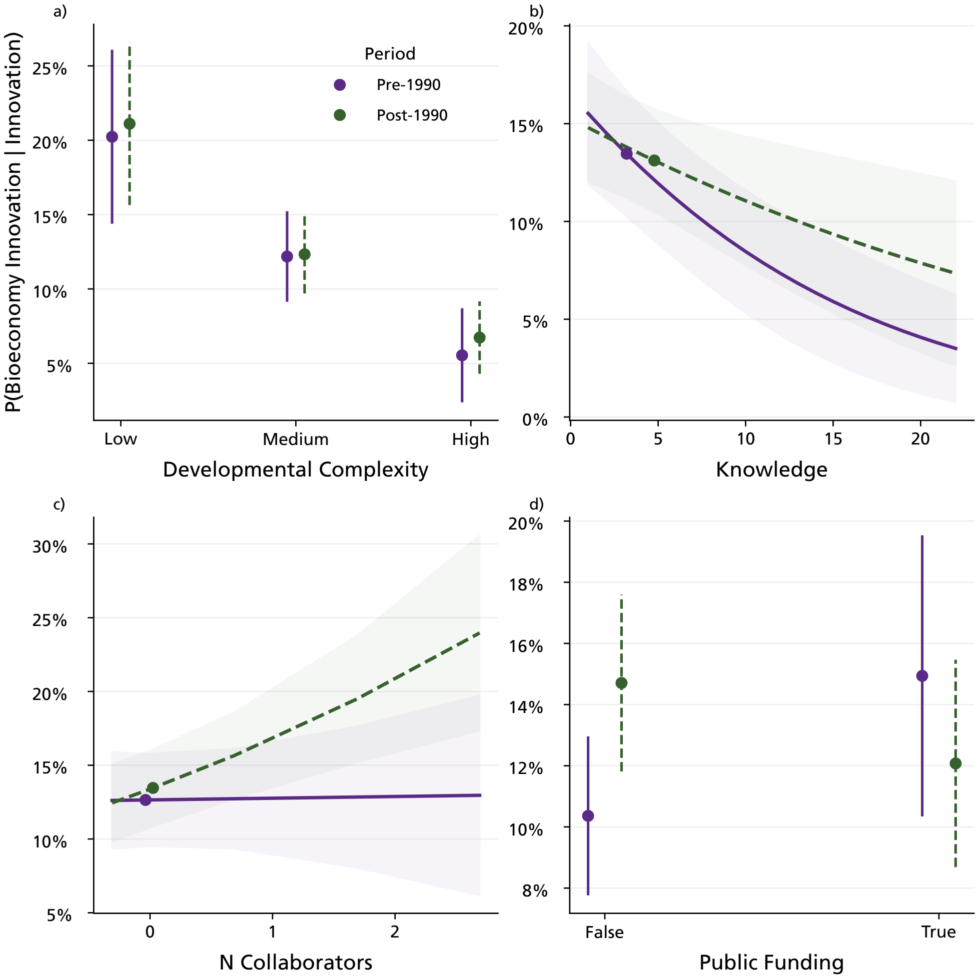

Figure 8: **Predicted Probabilities of Bioeconomy Innovation by Key Predictors.** Predicted probabilities comparing pre-1990 (solid purple) and post-1990 (dashed green) periods. Panel a) developmental complexity, panel b) knowledge diversity, panel c) number of collaborators, panel d) public funding. For continuous predictors: dots show sample means, shaded areas show 95% CIs. For categorical predictors: error bars show 95% CIs. Panel b) and c) cover the 99th percentile of sample values, to avoid distortion from outliers. Other covariates at representative values.

adapting from mature optimization to entrepreneurial exploration. New entrants struggled to gain footing despite two surges (1970s and 2000s), with most producing single innovations before exiting technological development. However, the locus of bioeconomy innovation increasingly shifted beyond core forestry sectors during the product expansion period, with outside-core innovations averaging approximately 50% of the sample by the 2010s. This shift was driven by new biomass-valorization firms rather than incumbent diversification, but whether it reflects a durable structural change requires further investigation; the rising ratio coincides with a broader contraction in Swedish manufacturing innovation that may have suppressed core-sector output disproportionately. The pattern aligns with Peltoniemi (2011)'s understudied prediction that mature industries may enable the birth of technologically related new industries, and tracing how knowledge spillovers from mature sectors seed adjacent ones represents a productive direction for future work. The new outside-core entrants built on cellulose and lignin chemistry refined over decades in pulp and paper processing, with knowledge traveling through academic networks rather than through firm-level diversification.

Third, empirical evidence contradicts most conventional assumptions about bioeconomy innovation. Among successfully commercialized innovations, bioeconomy innovations were associated with lower developmental complexity and narrower knowledge bases than other innovations. Collaboration intensity showed no association before 1990 but became positively linked to bioeconomy innovation during the product expansion period, providing partial support for the literature's emphasis on collaborative development. Public funding's association reversed entirely: positive during component optimization, negative during product expansion. Both results are period-specific, suggesting that bioeconomy innovation characteristics depend on the life cycle stage rather than being inherent to the bioeconomy as such. Core arguments about requiring higher complexity or broader knowledge bases were directly contradicted by the data.

The forest-based bioeconomy is often presented as fundamentally different from conventional industries, requiring novel approaches and collaboration models. This study's historical evidence from Sweden suggests a more nuanced picture: mature forest industries responded to new technological opportunities by leveraging existing competencies to explore new product spaces. Rather than demanding unprecedented complexity or knowledge diversity, successful bioeconomy innovations drew on narrower, more focused capabilities, though the growing role of collaboration after 1990 suggests that the product expansion phase placed different demands on inter-organizational coordination than the preceding optimization period. For policy, the implication is direct: bioeconomy strategies calibrated to a single set of innovation characteristics risk misallocating resources across industries at different life cycle stages. Whether these patterns hold in other forest-rich economies, in non-forest bioeconomy sectors, or reflect mechanisms specific to Swedish forestry remains for future research, but the broader lesson stands—historical evidence from commercialized innovations is a more reliable guide to bioeconomy policy than expert consensus built without it.

Code Availability

The data preparation and count statistic analysis used the polars package (Vink et al., 2024) in Python. Statistical modelling was conducted using the `statsmodels` (Seabold and Perktold, 2010) and `marginaleffects` (Arel-Bundock et al., 2024) package. Figures also used `matplotlib` (Hunter, 2007). The code and data needed to reproduce the analysis are archived at Zenodo (DOI: 10.5281/zenodo.18928826).

AI Statement

During the preparation of this manuscript Anthropic's Claude Sonnet 4.5 and Opus 4.6 were used to improve the structure, clarity, and flow of the argument. They were also used in refactoring code.

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Appendix

Table A1: Sample attrition from full SWINNO sample to estimation sample.

	Total	Bioeconomy	Non-bioeconomy
Full SWINNO sample	4972	649	4323
Estimation sample	4183	547	3636
Observations dropped	789	102	687
Observations dropped by variable			
Knowledge	631	78	553
Public Funding	122	10	112
Path Dependency	79	10	69
Developmental Complexity	23	6	17
Oil Prices (ln) 5-MA	4	1	3
Wood Prices (ln) 5-MA	4	1	3
Firm	3	0	3
Δ Oil Prices (ln)	1	0	1
Δ Wood Prices (ln)	1	0	1

Counts are not mutually exclusive. Total attrition reflects listwise deletion.

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