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How to identify and interpret weak signals of change in the forest bioeconomy

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ABSTRACT

Weak signals, the first signs of a potentially emerging issue that could disrupt current trends and megatrends, are hidden among disconnected pieces of information. Analyzing weak signals can help decision makers generate preparedness and a rapid-response capacity for possible systemic changes in the forest bioeconomy, where weak signals have not been studied extensively. This exploratory study sought to understand how to identify and interpret weak signals of change that may have an impact on the forest bioeconomy. An international panel of experts in the forest bioeconomy and in foresight provided their views through a two-stage Real-Time Delphi method which utilized the multiple rounds of traditional Delphi and the instantaneous feedback of the Real-Time Delphi method. This study introduces four conceptual frameworks to use when searching for weak signals: Internal/external operating environment, the Multi-level perspective, the Three Horizons Framework, and Complexity theory. These conceptual frameworks were applied in the analysis of collected data with the aim of developing the theory and practice on how to identify and interpret weak signals. According to the results, observations beyond the traditional dominating operating environment and a combination of observations from various sources could help to identify weak signals that may affect the forest bioeconomy. The Real-Time Delphi insights suggest that weak signal analysis becomes stronger via collaboration and interaction between futures specialists and forest bioeconomy experts.

1. Introduction

Forest-based industries have undergone many changes in industrial structure and trade flows, especially due to megatrends or broad drivers of change such as globalization, the development of information and communication technologies, and climate and energy policy (e.g., Päteri et al., 2016; Korhonen et al., 2017; Laakkonen et al., 2022). Despite the influence of these megatrends, there are always fundamental uncertainties about the future. A focus on megatrends runs the risk that future changes will seem too certain and unambiguous, weakening actors' capacities to react to new or low-likelihood changes. Policy and business planners must also examine surprises and discontinuities, such as weak signals, which are signs of a potentially emerging issue that could disrupt current trends and megatrends (see e.g., Ansoff, 1975; Hiltunen, 2010). Weak signals are the first symptoms of change, disconnected pieces of information that at first appear to be background noise but can later be recognized as part of a significant future change (e.g., Hiltunen, 2010; Lesca and Lesca, 2014). The analysis of weak signals complements trend analysis and can be used to broaden our understanding of the future, especially in the forest bioeconomy, where weak signals have not been studied extensively.

This study focuses on signals of change that may have an impact on the forest bioeconomy. The forest bioeconomy is a part of the bioeconomy that is limited to forests and their use, whereas bioeconomy can be a controversial concept with different interpretations and uses (e.g., Kleinschmit et al., 2014; Pülzl et al., 2014; Giurca, 2020; Ranacher et al., 2020). To identify possible weak signals of change affecting the forest bioeconomy, it is essential to structure changes in the operating environment and understand their dynamic complexity. In this study, the forest bioeconomy operating environment is defined as a broad internal and external environment that can be affected by possible signals of change. In this context, analyzing weak signals can help generate resilience and a rapid-response capacity for possible systemic or structural changes.

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Structural changes in the operating environment of the forest bioeconomy have been studied in recent years (e.g., Hansen et al., 2013; Hetemäki, 2014; Hetemäki et al., 2017). For weak signals in the forest bioeconomy, it is important to examine whether there are features in the operating environment where the first symptoms of change and emerging issues are particularly important from the perspective of significant transitions. Transitions in the operating environment of the forest bioeconomy may be related to sustainability, for example, which has been a research trend in recent years (e.g., Päteri et al., 2016; Patterson et al., 2017).

In the case of the future forest bioeconomy, many forest science foresight studies have considered sustainability and other transitions (e.g., Toppinen et al., 2017; D'Amato et al., 2020; Luoma et al., 2022). Although the above futures-oriented forest bioeconomy research has yielded useful results, research focusing on weak change signals affecting the forest bioeconomy has been limited. Strengthening this research, which is the purpose of this exploratory study, can help structure the phenomenon as a basis for more concrete follow-up studies in the future.

This study furthers the theory and practice of identifying and interpreting weak signals of change in the forest bioeconomy. For this purpose, futures research lends useful concepts for this study. Futures research is a transdisciplinary field of study that uses a wide range of social science methods combined with creativity and imagination to develop and explore possible, plausible, and preferable futures (Bell, 1996, 1997). These methods in foresight processes range from expert-based to participatory, quantitative to qualitative, and evidence-based to creativity- and imagination-based methods (Popper, 2008; Gordon and Glenn, 2009).

The purpose of this study is to investigate how to identify and interpret weak signals of change affecting the forest bioeconomy. Two research questions are examined: (i) What is the nature of future changes affecting the forest bioeconomy? (ii) How can weak signals of change be identified and interpreted in the forest bioeconomy operating environment? The purpose of the first research question is to structure the nature of future changes that may have an impact on the forest bioeconomy. Thereafter, the purpose of the second research question is to examine the identification of weak signals as part of a broader analysis of future changes. To answer the research questions, this study applies a two-stage Real-Time Delphi method to collect expert views on how to identify and interpret weak signals. In addition, this study introduces four conceptual frameworks to use when searching for weak signals. These conceptual frameworks connect the views of experts with the purpose of the study, aiming to investigate how to identify and interpret weak signals.

2. Theoretical background

2.1. Weak signals

A range of futures research terms is used to describe change, such as megatrends, trends, emerging issues, and drivers of change. Regardless of the terms used, all types of change involve inherent uncertainties. Analyzing weak signals – the first signs of a potentially emerging issue – can help generate a rapid-response capacity for possible structural or systemic changes.

The concept of weak signals originated in the 1970s, when Ansoff (1975) created a method for systematic observation of changes in the operating environment that could lead to crises. Since the 1970s, the definition of weak signals has expanded, and they are now referred to using many different terms, including silent signals, seeds of change, and early warning signs (e.g., Hiltunen, 2006; Miller et al., 2012).

The detection of weak signals has been studied extensively in previous futures studies (e.g., Toivonen, 2004; Kuosa, 2010; Holopainen and Toivonen, 2012; Eckhoff et al., 2014; Mühlroth and Grottke, 2018). Hiltunen (2010) defines a weak signal as the first symptom of a change or a sign of a rising issue or topic that may be significant in the future. Weak signals can be detected through all human senses, as they can be seen, heard, smelled, felt, or even tasted (Heinonen and Hiltunen, 2012; Lesca and Lesca, 2014). Consequently, weak signals can be defined in terms of three components: 1) the phenomenon itself, 2) the signal that indicates a phenomenon (i.e., news, image, service, product, or event), and 3) interpretation, i.e., how the signal is received, how it is linked to the interpreter's own view and worldview, and how it is used (e.g., Heinonen and Hiltunen, 2012; Ilmola-Sheppard, 2014; Lesca and Lesca, 2014; van Veen and Ortt, 2021).

The emerging future may announce itself with a variety of diverse types of signals but not necessarily weak ones. There are categorical differences between future phenomena, depending on their likelihood of occurrence and potential impact or significance. As illustrated in Fig. 1, if the probability of a phenomenon occurring is low but the importance of the phenomenon is high, the phenomenon may be a weak signal (Holopainen and Toivonen, 2012; Ejdys, 2017). Similarly, if the importance of a phenomenon and the probability of its occurrence are low, the phenomenon can be called "meaningless noise" (Fig. 1). Trends and megatrends, however, occur in situations where the probability of the phenomenon occurring is high (Holopainen and Toivonen, 2012, Ejdys, 2017) (Fig. 1).

Despite the challenges of detecting weak signals, there are similarities in their characteristics. Common features of weak signals include novelty, surprise, challenge, relevance, and delay, in which case a weak signal indicates something not yet significant (Hiltunen, 2010). This last characteristic is also mentioned by Lesca and Lesca (2014), as they define a weak signal as information that may appear insignificant or that is hidden among other information. In conclusion, weak signals are difficult to identify and understand because they do not force themselves to be exposed and are therefore classified as "weak" (Lesca and Lesca, 2014).

2.2. Conceptual frameworks to use when searching for weak signals

2.2.1. Rationale

Since identifying and interpreting weak signals is challenging, guidance is needed to systematically search for signals of change that are

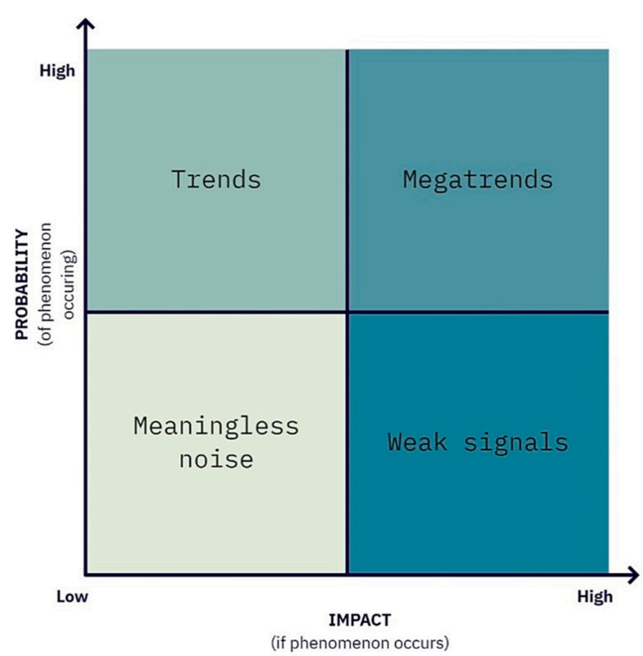

Fig. 1. Categories of future phenomena based on likelihood and impact (Figure adapted from Holopainen and Toivonen, 2012, Ejdys, 2017).

not clear in the present time. In addition, since there are no comprehensive guidelines for the identification and interpretation of weak signals, conceptual frameworks are needed to target the work with weak signals. According to the principles of futures research, essential dimensions in futures research are complexity and systems thinking (e.g., Bell, 1996, 1997; Leonard and Beer, 2009). These perspectives help structure thinking related to weak signals.

Four conceptual frameworks are used in this study. First, the operating environment of a particular field, such as the forest bioeconomy, can be viewed through a framework of the strategic research concepts of internal and external environments (e.g., Alkhafaji, 2003; Scearce et al., 2004). Second, weak signals can also be interpreted as part of a systemic change through the multi-level perspective (MLP) on socio-technical transitions (Geels, 2002; Geels and Kemp, 2007). Third, the Three Horizons Framework (Curry and Hodgson, 2008) is helpful for understanding and classifying the timing and potential evolution of change phenomena at hand. Fourth, complexity theory is an important ontological assumption in the methods of futures research, i.e., that the world is complex and full of different intersections (e.g., Anderson, 1999; Manson, 2001).

The conceptual frameworks chosen for this study are part of the concepts of systemic analysis and futures research. These four frameworks have been chosen because they have been widely used to develop and explore futures, and they bring out the uncertainty and cross-effects related to the future and the complexity connected to it (Bell, 1996, 1997, Leonard and Beer, 2009). In addition, these conceptual areas bring out a clear analysis that the signals of change can be close or further away from the system under consideration, even if they are not in that system itself (Leonard and Beer, 2009).

2.2.1.1. Internal/external operating environment. To identify possible weak signals in the forest bioeconomy, it is essential to structure changes in the operating environment and understand how they function. In general, operating environments appear in multiple dimensions, such as temporal, geospatial, or cultural dimensions, that can provide meaning to environmental actions or events (Tolone et al., 2013). The operating environment is a dynamic reflection of changes in environmental conditions and impacts (Alkhafaji, 2003; Tolone et al., 2013). Behind operating environments, there are also relevant patterns and consequence relationships that occur in the background and explain observable behaviors and changes in the environment (Tolone et al., 2013).

The operating environment can be divided into internal and external environments (Alkhafaji, 2003, Scearce et al., 2004). In the case of the forest bioeconomy, the internal operating environment refers to the immediate working environment, which includes forces of change such as the community, partners, customers, and competitors. Correspondingly, the external operating environment refers to the contextual environment, which encompasses broad driving forces such as social values, geopolitics, governance, sustainability, and technology (Alkhafaji, 2003, Scearce et al., 2004). In "outside-in thinking", external changes, such as seemingly insignificant technological developments in other fields, may play a vital role, which over time can profoundly affect the operating environment (Scearce et al., 2004). Examining the internal working environment and its external contextual environment can evoke more open and imaginative views about various possible weak signals that might not otherwise be visible (Scearce et al., 2004).

2.2.1.2. Multi-level perspective (MLP). The operating environment of the forest bioeconomy includes numerous transitions that could lead to systemic change, with most pointing to transformations towards sustainability (Patterson et al., 2017). A variety of conceptual approaches have been developed to understand and analyze societal transformation processes. These transitions include socio-technical transitions (e.g., Geels, 2002; Geels and Schot, 2007), social-ecological transitions towards sustainability (e.g., Westley et al., 2011; Olsson et al., 2014), transformative pathways to sustainability (e.g., Leach et al., 2012, 2013), and transformative adaptation (Pelling, 2011; O'Brien and Selboe, 2015).

The functions of the operating environment can be viewed from a socio-cultural perspective. For example, weak signals can be interpreted as part of a systemic change through the MLP on socio-technical transitions (Geels, 2002; Geels and Kemp, 2007). According to the MLP, the interaction of the operating environment (macro, i.e., landscape level), the operating model (*meso*, i.e., regime level), and the functions outside the developing system (micro, i.e., niche-innovation level) enables system change (Geels and Kemp, 2007; Geels and Schot, 2007). The basic idea is that the incompatibility of the operating environment and system acts as a driver for change, which creates pressures for system reform and the breakthrough of new innovations at the developing system level (Geels, 2002; Geels and Kemp, 2007; Geels and Schot, 2007).

The MLP on sociotechnical transitions is used to illustrate several types of changes in the operating environment. In the MLP, the landscape level is an external socio-technical environment, which includes megatrends or shocks. Correspondingly, there are several socio-technical systems at the regime level, which are often closed, making it difficult for new innovations to break into (Geels and Kemp, 2007, Geels and Schot, 2007). At the niche-innovation level, new innovations tend to break into operating models, for example, when the operating environment and system act as drivers. Such drivers can be wild cards, defined as abrupt and low-probability events that are expected to have substantial consequences (Hiltunen, 2006; Bengston, 2023). Although weak signals can be set at the niche-innovation level of the MLP on socio-technical transitions, anticipating a weak signal is challenging. Geels and Schot (2007) used the MLP model to describe historical changes retrospectively but not future changes. However, the MLP model has recently been used in futures studies for anticipatory purposes (Vähäkari et al., 2020).

2.2.1.3. The Three Horizons Framework. Future changes and weak signals can be observed through the Three Horizons Framework, a model that allows for the combination of different futures and strategic methods as needed (Sharpe and Hodgson, 2006; Curry and Hodgson, 2008). The Three Horizons Framework highlights three separate ways of looking to the future, with each way affecting what is considered a successful system (Hodgson and Midgley, 2015).

The Three Horizons Framework is a qualitative foresight tool for structuring profound long-term change processes (Sharpe et al., 2016; Jordan, 2021). It is based on the idea that many organizations, technologies, and policy decisions have stages of initiation, growth, success, and decline in their life cycles (Sharpe and Hodgson, 2006; Jordan, 2021). The Three Horizons Framework follows the idea of successively displacing cycles that can be seen as waves of change (Sharpe and Hodgson, 2006; Sharpe et al., 2016; Jordan, 2021). These waves and processes of change are needed to maintain strategic effectiveness in the context of change. In the Three Horizons Framework, the time interval for each horizon can vary from a few years to several decades. From a strategic point of view, an important aspect is not the time scale of structural change but rather the qualitative difference within each horizon (Jordan, 2021).

The Three Horizons Framework focuses on the strategic efficiency of the system, as well as the evolution of the environment over time (Sharpe and Hodgson, 2006, Jordan, 2021). This approach reflects the coexistence of three horizons from the present to the future. In this way, alternative futures can be visualized, and ideas about continuity and innovation can be expressed (Jordan, 2021). According to Curry and Hodgson (2008), the first horizon (H1) illustrates the gradual decline of the dominant system that occurs in parallel with the Horizon of Innovation Processes (H2) and the Transformation Process Horizon (H3), culminating in a new dominant system (Sharpe et al., 2016, Jordan, 2021). The Horizon of Transformation Processes makes better use of the opportunities offered by a changing environment (Jordan, 2021).

Weak signals may be found on the Horizon of Innovation Processes (H2) and the Transformation Process Horizon (H3). However, the identification of weak signals is often ambiguous. Weak signals can be difficult to identify because, for example, their actual signal time or time to become a trend is so far in the future that it is not yet possible to capture relevance. This is especially significant in the complex operating environment of the forest bioeconomy because identifying and interpreting weak signals has not been studied extensively.

2.2.1.4. Complexity theory. Identifying weak signals of change in the forest bioeconomy operating environment can be difficult because they are part of complex systems. Even when a potential weak signal is detected, uncertainties and challenges remain because it is not possible to know whether the signal is weak or, for example, is a silent sign on another topic (Hiltunen, 2010). For example, when wild cards appear, there is the possibility that the system will be disrupted, and a weak signal can become a strong signal (Griol-Barres et al., 2020). A change in a certain part of the system emphasizes the importance of looking at performance in terms of the entire system rather than its components (van Kerkhoff, 2013).

In systems thinking, it is essential to understand the diverse parts and the interactions of these parts (Arnold and Wade, 2015). Complexity theory emphasizes the interaction between the various parts of the system (e.g., Anderson, 1999; Manson, 2001). A change in a system affects both a specific part of the system and the entire system (Morel and Ramanujam, 1999). Complexity theory deals with complex systems that do not have simple causalities and reveals that complex systems can produce unexpected outcomes due to choices and interactions (Morel and Ramanujam, 1999). Combined with weak signals of change, possible, plausible, and preferable futures can be explored more creatively.

To identify weak signals affecting the forest bioeconomy, it is important to understand the complexity of the operating environment. In addition to complexity theory, the three other conceptual frameworks presented earlier help in structuring thoughts when searching for weak signals. These four frameworks can improve understanding of the complexity of future changes and how to start identifying and interpreting weak signals of change affecting the forest bioeconomy operating environment.

3. Materials and methods

3.1. Real-Time Delphi method

Since the first Delphi study was published in 1964 by the RAND corporation (Gordon and Helmer, 1964) and the method was made known to a wider audience in 1975 (Linstone and Turoff, 1975), the Delphi method has been used in many fields. In futures research, the Delphi method is a general data collection method in the form of an anonymous, multi-round, interactive interview or questionnaire in which the purpose of the interaction process is to assess possible future developments from the statements of a group of experts (e.g., Linstone and Turoff, 1975; Rowe and Wright, 2001). The Delphi method is useful when the research object is complex, when the content or solution is unknown at present, or when assessing the long-term development of society or finding a potential action program (e.g., Gordon and Helmer, 1964; Gupta and Clarke, 1996; von der Gracht et al., 2011).

Common features of the Delphi method are anonymity, multiple rounds, and feedback (Rowe and Wright, 2001). The aim of anonymity is for experts to present their genuine views and insights about the topic, without the opinions of other experts influencing the formation of the consensus opinion in the panel (Rowe and Wright, 2001). The purpose of multiple rounds in the Delphi method is to allow experts to revise their views from previous rounds based on feedback from other participants (Rowe and Wright, 2001).

Real-Time Delphi allows an interactive and around-the-clock alternative to traditional Delphi in an online environment (Gordon and Pease, 2006). Real-Time Delphi has the advantage of accelerating and enhancing decision making, as the process is not interrupted to analyze intermediate results (Gordon and Pease, 2006; von der Gracht et al., 2011). Another strength of Real-Time Delphi is its interactivity, as feedback to an expert panel that participates anonymously is direct, as is the opportunity for experts to debate with each other (Gordon and Pease, 2006). Lastly, Real-Time Delphi simulates a hypothetical decision-maker to whom relevant information influencing decision-making is provided (Gordon and Pease, 2006).

In forest sciences and in forestry research, the Delphi method is widely used (Heiskanen et al., 2022). For example, the Delphi method has been used for analyzing, assessing, prioritizing, comparing, and exploring different research topics in the field of forest sciences (e.g., Qu et al., 2010; Lehtonen and Tykkyläinen, 2014; Näyhä and Pesonen, 2014; Korhonen et al., 2015; Devaney and Henchion, 2018; Brunnhofer et al., 2020; Heiskanen et al., 2022). However, this exploratory study aims to utilize the multiple rounds of traditional Delphi and instantaneous feedback of the Real-Time Delphi method to collect expert views on how to identify and interpret weak signals.

3.2. Expert matrices

A Real-Time Delphi exercise was conducted in two stages through the eDelphi software (eDelphi, 2023) among a group of experts specializing in futures research and the forest bioeconomy. As is typical in Delphi research, this study started by planning the selection of an expert panel. The selection of panel members involved the creation of two expert matrices: forest bioeconomy experts (Table 1) and futures research and foresight specialists (Table 2). In the expert matrix, stakeholder categories are in the columns, and expertise is in the rows to outline the potential futures as comprehensively as possible. In general, stakeholders in the expert matrix represent interest groups that have a significant position in society. For this study, columns of the expert matrices described the stakeholders (organizations), and the rows described the areas of expertise (Tables 1 & 2). The stakeholders in the expert matrices were divided into two main categories: Research & Development and Innovation (RDI) and Organizational Management. These two were then divided into five subcategories: science and education institutions, RDI companies and departments, private firms and businesses, publicly funded organizations, and non-governmental organizations (NGOs) and associations (Tables 1 & 2).

The expert matrices were divided into two main categories according to the experts' area of expertise – forest bioeconomy, and futures research and foresight, which contained three subcategories each. The forest bioeconomy areas of expertise were (1) forests and forestry, (2) processing, refining, and products, and (3) markets and consumers (Table 1). The futures research and foresight column also had three areas of expertise: (1) societal/socio-cultural foresight, (2) technology foresight, and (3) creativity and imagination (Table 2).

Seventy experts were compiled in the expert matrices, of which 51 were contacted by email, and 16 agreed to participate in the study. Of these 16 experts, 11 (6 forest bioeconomy experts and 5 futures research and foresight specialists) finally participated in both eDelphi stages (Tables 1 & 2). Participants were from Finland (7), Canada (2), Sweden (1), and Uruguay (1). The remaining 19 experts in the matrices were not contacted when it was felt that a sufficient expertise had agreed to participate in the study.

The purpose of this study was to gather sufficient expertise, and not to fill all the cells of the matrices. Sufficient expertise was obtained when all rows of the matrices had expertise and when both tables were added together, the result was that each column also had experts represented. In addition, sufficient expertise was obtained when international experts were represented. Identifying and interpreting weak signals can be

Table 1
Anonymized expert matrix for the Real-Time Delphi approach (forest bioeconomy). A total of 6 forest bioeconomy experts participated in both eDelphi stages. The expertise of these experts covered the following 7 cells in the matrix.

	Stakeholders				
	Research, development, and innovation (RDI)		Organizational management		
Area of expertise	Science & education institutions	RDI companies and departments	Private firms and businesses	Publicly funded organizations	NGOs and associations
Forest bioeconomy					
• Forests & forestry			✓	✓	✓
• Processing, refining & products	✓				
• Markets & consumers	✓		✓	✓	

Table 2
Anonymized expert matrix for the Real-Time Delphi approach (futures and foresight). A total of 5 futures and foresight experts participated in both eDelphi stages. The expertise of these experts covered the following 6 cells in the matrix.

	Stakeholders				
	Research, development, and innovation (RDI)		Organizational management		
Area of expertise	Science & education institutions	RDI companies and departments	Private firms and businesses	Publicly funded organizations	NGOs and associations
Futures and foresight					
• Societal/Socio-cultural foresight		✓		✓	
• Technology foresight	✓	✓			
• Creativity & imagination			✓	✓	

considered a global activity and for this reason experts were recruited from four different countries and three different continents.

3.3. First Real-Time Delphi stage

After the construction of the expert matrices, the first stage of Real-Time Delphi was planned and built on edelphi.org. Descriptive questions that aimed at the future were open-ended, were designed to share opinions, and were created as deemed important for the first eDelphi stage. In this study, the aim was to collect experts' responses from different perspectives and capture interactive discussions.

The first Real-Time Delphi stage focused on future changes. The purpose was to be a starting point for examining how weak signals of change could be identified and interpreted in the forest bioeconomy operating environment, as weak signals are defined as the first symptoms of change (e.g., Hiltunen, 2010). Therefore, the focus of the first stage was to examine the nature of the various changes affecting the forest bioeconomy.

The experts were asked 6 open-ended questions, of which three were general questions about future changes (Questions 1, 3, and 5) and the other three were questions applicable to the forest bioeconomy (Questions 2, 4, and 6) (Appendix A). The purpose of dividing the questions was to stimulate discussion on a general level and from the perspective of the forest bioeconomy. Questions 1, 3, and 5 were general-level questions on the background of the topic, while questions 2, 4, and 6 took a stand on what the previous questions meant in the broad environment in which the forest bioeconomy operates. In addition, the purpose of the questions in the first Real-Time Delphi stage was to structure the nature of future changes to deepen the discussion of weak signals for the next stage.

The first stage was conducted in early September 2022 during a 10-day period (Sep 5, 2022 – Sep 14, 2022) using eDelphi software (eDelphi, 2023). Data were collected using the eDelphi comment section, which was an avenue to provide, supplement, comment on, and discuss answers from all experts. To stimulate discussion, all responses and comments were visible to the participants and were open to comments and suggestions. However, consistent with the Delphi method, answers, and comments were anonymous to both the participants and the researchers who conducted the study.

The first stage ended with a review of the data obtained from the expert answers and discussions. The answers were categorized using NVivo qualitative data analysis software (Lumivero, 2023). The categorization was conducted in two parts. First, the data collected from the first stage were categorized by autocoding, after which the material and answers were reviewed again with the aim of removing any autocoding errors made by the software. The categorization's purpose was to summarize the discussions in the first stage to finalize the questions for the second stage.

3.4. Second Real-Time Delphi stage

Like the first stage, the second Real-Time Delphi stage was conducted in edelphi.org during a 10-day period in September 2022 (Sep 21, 2022 – Sep 30, 2022). The questions focused on weak signals of change. The second stage was a continuation of the first, with the goal of deepening the discussion of identifying and interpreting weak signals of change. In this stage, weak signals were defined as disconnected pieces of information that initially appear to be background noise but could be recognized as part of a significant future change by viewing them through a different frame or connecting them with other pieces of information (e.g., Hiltunen, 2010; Lesca and Lesca, 2014). The theme of this stage was to examine how weak signals of change could be identified and interpreted in the broad environment in which the forest bioeconomy operates.

As in the first stage, the experts were asked six open-ended questions, of which three were general questions about weak signals (Questions 1, 3, and 5), and the other three were questions applicable to the forest bioeconomy (Questions 2, 4, and 6) (Appendix B). The purpose of dividing the questions into general-level and forest bioeconomy questions was to stimulate discussion between forest experts and futures specialists. The questions in the second stage were based on the first-stage answers and discussions. Like the first stage, the second Real-Time Delphi stage was divided into two phases: 1) answering the questions and 2) commenting on and discussing the answers of other

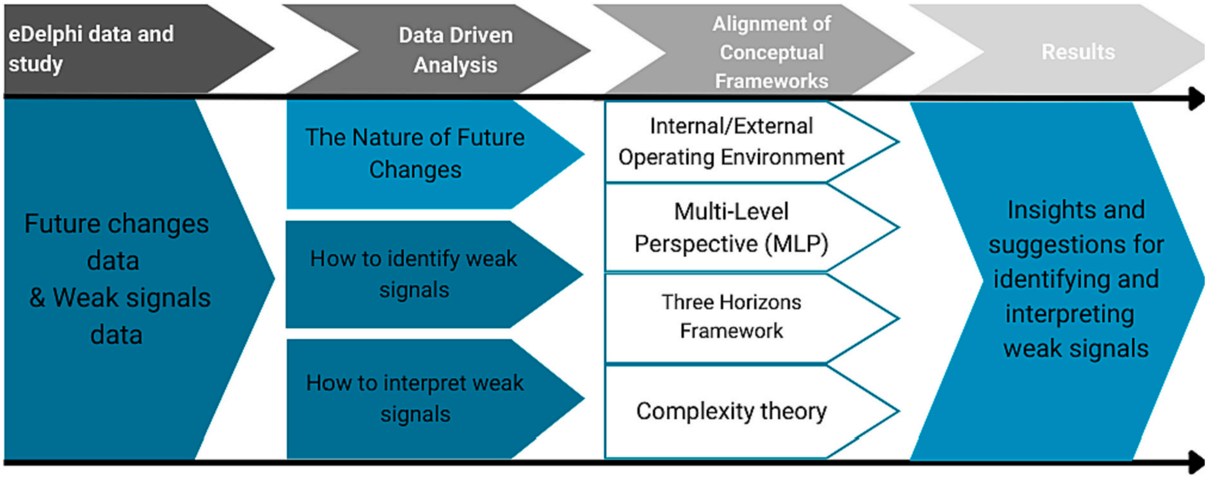

Fig. 2. Analysis using NVivo qualitative data analysis software.

participants.

Interactivity and discussion played a key role in the second stage. While the objective in the first stage was to frame the topic and find answers to the first research question, the second stage pursued open discussion for finding and interpreting weak signals affecting the forest bioeconomy. To allow the openness, interactivity, and flexibility of the method, participants could present their ideas and justifications by commenting on the answers. Through this, agreements, constructive criticisms, and observations of each other's insights were demonstrated. In addition, the questions in both stages were intended to be as open and flexible as possible so that the answers could also be viewed through different conceptual frameworks in the analysis phase.

3.5. Analysis

The Real-Time Delphi exercise ended with the analysis of the collected data (future changes data and weak signals data). The analysis was divided into two parts: data-driven analysis and the alignment of conceptual frameworks (Fig. 2). The data were analyzed separately by two of the authors using NVivo qualitative data analysis software (Lumivero, 2023), thereby reducing the subjectivity of the analysis. In the data-driven analysis, the data were coded into three categories according to the research questions: (1) The nature of future changes, (2) How to identify weak signals, and (3) How to interpret weak signals (Fig. 2). The data were categorized in this part in preparation for the next step of applying the conceptual frameworks. The data-driven analysis ended with a discussion among the researchers conducting the analysis about the coding results.

The data were then interpreted through the four conceptual frameworks described earlier: (1) internal / external operating environment, (2) Multi-level perspective (MLP), (3) the Three Horizons Framework, and (4) Complexity theory. These conceptual frameworks were applied using NVivo qualitative data analysis software, as the selected theories were a tool for understanding and classifying the data into distinct categories. The purpose of the classification was to connect the views of experts to conceptual frameworks, aiming to collect insights and suggestions on how to understand the nature of future changes and how to identify and interpret weak signals. After the data were coded into categories, they were annotated as to why the specific response was coded under a certain conceptual framework. Like the data-driven analysis, the alignment of conceptual frameworks ended with discussions among the researchers. The purpose of the joint analysis and discussion was to find relevant information from the data using a systematic procedure. Lastly, to present the results concisely and understandably, the findings that emerged from the data were classified and presented in a series of tables according to the research questions (Fig. 2). After the analysis, the collected data were anonymized and permanently stored with open access principles in the Zenodo data archive (zenodo.org).

4. Results

4.1. The nature of future changes

The two phases of analysis (data-driven analysis and alignment of conceptual frameworks) allowed the researchers to answer the two research questions accordingly. To deeply understand the nature of future changes in the forest bioeconomy operating environment, the results were concisely summarized in two tables, one of which classified the nature of various changes affecting the forest bioeconomy (Table 3), and the other classified the observations found in the data using the conceptual frameworks (Table 4). In both tables, excerpts from the data illustrate the justifications for the classifications.

4.2. How to identify and interpret weak signals

The purpose of the second research question was to examine how weak signals of change can be identified and interpreted in the forest bioeconomy operating environment. To identify weak signals in the forest bioeconomy operating environment, the results are summarized in two tables. The first table classifies the nature of various weak signals affecting the forest bioeconomy and how weak signals of change could possibly be identified in the forest bioeconomy operating environment (Table 5), and the second classifies the observations found in the data using the conceptual frameworks (Table 6). In both tables, excerpts from the data illustrate the justification for the classification.

In addition to identifying weak signals, the purpose of the second research question was to examine how weak signals of change could be interpreted in the forest bioeconomy operating environment. For the interpretation of weak signals, the results were illustrated with the help of a summary table that classifies the observations found in the data using conceptual frameworks described earlier (Table 7). In the summary table, excerpts from the data illustrate the classifications.

Table 3
Summary of understanding of future forest bioeconomy changes and the nature of various changes affecting the forest bioeconomy operating environment.

	Classified findings that emerged from the data	Data excerpts
Thematic areas for identifying possible future changes that may affect the forest bioeconomy:	• **Strategies and policies** (e.g., sustainability questions and the role of forests, social-ecological sustainability) • **Technology** (e.g., new technological developments can provide insight into what is possible) • **Trends** (e.g., development of prices, consumer behavior, sustainable development)	• "*As a crude first attempt to identify changes to the forest bioeconomy, I might look at any new process, product, or technological development that creates new paths within that model, or immediately adjacent to it.*" • "*Apart from economic factors, possible future changes can be identified and monitored by analyzing their impact on nature and environment.* E.g.*, are the identified changes to enhance sustainable development (economic, ecological, social) or pose risk to that.*"
Channels, platforms, and sources of information where those possible future changes may be identified:	• **Social sources** (e.g., social media, political debate, web discussion) • **Digital sources** (e.g., conventional media, web discussion, statistics) • **Research** (e.g., research institutions, professional media, think tanks, reports, statistics)	• "*The early signs of a rising paradigm can be found from social media and other public discussion forums.*" • "*The role of social media can be more and more important in identifying emerging themes.*" • "*Social media, conventional media, policy debates, schools, and universities. Tricky part is who can follow the enormous amounts of 'data' that reflect the coming changes. Artificial intelligence (AI) applications perhaps?*"
Features, and characteristics of future changes that may influence the forest bioeconomy:	• **Blurring sectoral boundaries** ("cross-sectoral" nature of the forest bioeconomy) • **Sustainability** (the role of forests in sustainability questions and the use of forests) • **Climate change** (forest bioeconomy has the potential to mitigate climate change, but its potential is also dependent on it)	• "*the emphasis of the 'cross-sectoral' nature of the forest bioeconomy.*" • "*Blurring sectoral boundaries (forest, energy, agriculture, food, chemistry, medicine) ≥ new products, new potential.*" • "*In long-term it is the necessary for 'the forest bioeconomy sector' to show and tell that it's contribution to global megatrends (biodiversity loss, climate change, resource scarcity) is positive.*"

Table 4
Summary of understanding the nature of future changes in the forest bioeconomy operating environment through four conceptual frameworks.

	Classified findings that emerged from the data	Data excerpts
Internal/external operating environment:	• The external operating environment could improve the understanding of the changes that can happen internally (cross-sectoral understanding is needed).	• "*To understand what really will be happen in the forest bioeconomy, a deep understanding of crosscutting sectors (energy, agriculture, food, chemistry, medicine) and what is going there (technologies, products, resources, consumption habits) is needed.*"
Multi-level perspective (MLP):	• Changes could appear in every level of MLP, but future changes are harder to understand as they are more complex. • Future changes could appear in niche innovations or even in regime and landscape levels. For example, the landscape level could add pressure to an existing regime, causing change.	• "*The most important criteria for identifying possible future changes should be social-ecological sustainability.*" • "*The growing global population, and their rights to basics (food, energy, education) strengthens even more economic-sociocultural dimensions of sustainability.*" • "*Production, demand, and consumption are in transformation. Simultaneously, high external pressure,* e.g.*, EU biodiversity conservation, may change the governance of forest bioeconomy radically.*"
Three Horizons Framework:	• Future changes might appear first in Horizon 2 as disruptive innovations. • New technologies and innovations in Horizon 2 could aid the understanding of Horizon 3 and early signs of a new dominant system.	• "*New technological developments can provide insight into what is possible, and those possibilities will certainly influence future directions.*" • "*Demand and product development may change the demand of wood and ecosystem services. New products can be based on a totally different technology and philosophy than today's product.*"
Complexity theory:	• The complexity brought by the entire bioeconomy sector poses challenges in understanding potential changes, as it focuses on sustainability.	• "*The simplified solutions that politicians like cannot solve the complex problems we are facing.*" • "*The sustainability and potential to deliver of the forest bioeconomy is called into question by various parties, such as NGO's, environmental administration, some part of science community.*"

Table 5
Summary of the identification of the forest bioeconomy weak signals and the nature of various weak signals affecting the forest bioeconomy operating environment.

	Classified findings that emerged from the data	Data excerpts
Criteria for identifying possible weak signals of change that may affect the future forest bioeconomy:	• **Behaviors and views of citizens/consumers** (e.g., consumer behavior, changing values) • **Outside the box thinking** (e.g., observations beyond the traditional, dominating operation environment, combination of observations from various sources)	• "*Our changing values, the relative significance/emphasis on some and not other values.*" • "*In this analysis, it would be relevant to understand multidisciplinary approaches.* I.e.*, not to interpret activist's observation directly through 'forestry lenses'. In this there is risk of a straight forwarding interpretation and losing some valuable/weak signals*"
Channels, platforms, and sources of information where those weak signals of change can be identified:	• **Social sources** (e.g., social media, web discussion, political debate) • **Multidisciplinary sources** (e.g., multidisciplinary discussions and initiatives outside of the "traditional" forest sector)	• "*Multidisciplinary discussion in science and practice may help oneself to open his/her eyes towards new type, beyond the tradition coming weak signals.*" • "*Commonly, research time span is relatively slow. This is a risk that in the really highspeed changing world the outcomes come too late, or they are not comprehensive enough in today's world*"
Features and characteristics of possible weak signals of change that may influence the future forest bioeconomy:	• **The ability to surprise** (e.g., strong emotional reactions) • **New thinking is often actively denied** (weak signals may appear in a different context, outside the forest bioeconomy)	• "*What gives them power is their ability to surprise. A weak signal should also present the potential for a significant departure from an existing, functioning system.*" • "*Weak signal in future forest bioeconomy is commonly something that is perceived somehow worth to deny among the traditional practitioners, science.*"

Table 6
Summary of the identification of weak signals in the forest bioeconomy operating environment through four conceptual frameworks.

	Classified findings that emerged from the data	Data excerpts
Internal/external operating environment:	• In the forest bioeconomy, weak signals could be identified both in internal and external operating environments, as well as outside the normal observation environment (as with future changes, cross-sectoral understanding is needed).	• "*Weak signals are commonly global,* i.e., *they appear first 'somewhere', beyond the 'normal observation environment'.*" • "*Many of the first signals of change are coming outside from the 'traditional' forest sector.*" • "*Weak signals frequently occur outside of the domain in question. Otherwise, they are less 'weak signals' and more 'notable developments'.*"
Multi-level perspective (MLP):	• Weak signals could appear in every level of the MLP (in niche innovations or even in regime and landscape levels). • As with future changes, it is important to look at the socio-cultural perspective to identify weak signals in the forest bioeconomy operating environment.	• "e.g., *EU is important in what is coming in the next 5–10 years. To go beyond that requires the following of global/local grand/micro phenomena.*" • "*The next weak signals could be related to socio-cultural equal access to materials. The current technology aims at providing same good for all people. The technology is not aiming at solving the grand challenge of very limited resources of one planet. This leads to the increasing tension between global south and north.*"
Three Horizons Framework:	• As with future changes, innovations, technologies, and forerunners of new ideologies in Horizon 2 could aid in understanding of Horizon 3 and early signs of a new dominant system.	• "*In weak signals we are trying to anticipate hints of becoming big changes.*" • "*I would emphasis the behavior analysis of forerunners. Their opinion may sound radical today, but the history is full of examples how some radical opinions have been institutionalized in time.*"
Complexity theory:	• When identifying weak signals, much interaction is observed among the different variables of the system. Since the forest bioeconomy is part of the environmental sector, other sectors, such as the economy, society, and technology, are a source of weak signals because they are highly interconnected.	• "*Citizens/consumers views are to a large extent affected by NGOs, industry information and media, so there it begins. How does the public adopt the differing views from the industry and the NGOs?*" • "*From forestry point of view, it is also interesting that citizens that do not own forests do have more and more opinions how forests are managed, and which are acceptable practices and which not in the future.*"

Table 7
Summary of the interpretation of weak signals in the forest bioeconomy operating environment through four conceptual frameworks.

	Classified findings that emerged from the data	Data excerpts
Internal / external operating environment:	• Interpretation of weak signals in the forest bioeconomy operating environment requires a multidisciplinary approach and outside-in thinking (weak signals blur sectoral boundaries).	• "*The essential issues are to really come out of the box to be able to read, interpret the surrounding societies at large, to note weak signals from different sectors that can be reflected directly and indirectly to future forest bioeconomy.*" • "*Multidisciplinary discussion in science and practice may help oneself to open his/her eyes towards new type, beyond the tradition coming weak signals.*" • "*Blurring sectoral boundaries (forest, energy, agriculture, food, chemistry, medicine) ≥ new products, new potential.*"
Multi-level perspective (MLP):	• When using MLP, it is possible to interpret wild cards as weak signals. Innovations tend to break into operating models, for example, when the operating environment and system act as drivers. • Interpreting weak signals is challenging but MLP can be used to describe historical changes.	• "*Climate change is a big wild card. It seems that much of the modelling around the bioeconomy is based on utilizing present bio-resources at a time when climate change is causing massive uncertainty in availability. The bioeconomy certainly has the potential to mitigate some of climate change, but its potential is also deeply dependent on it.*" • "*Nice idea to be able beforehand to identify disruptive technologies (Internet, mobile phone), but how likely this is? Rather, they are easy to notice afterwards.*"
Three Horizons Framework:	• Future changes and weak signals might appear first in Horizon 2. • Forerunners of new ideologies in H2 could aid in understanding H3 and early signs of a new dominant system.	• "*One needs to find indicators from the trends* etc. *and understand how they may impact the bigger picture.*" • "*New thinking is often actively denied and seen as an enemy that threats existing belief structures and individual worldviews and values. Weak signals can be found from those ideas, that are most violently resisted in social media.*"
Complexity theory:	• As with the understanding of future changes, the connection of networks in complex systems can aid the interpretation of weak signals.	• "*I think that one has to recognize the 'big' picture and how everything is connected to evaluate the impact to the 'whole' (social, economic, environmental, and human sustainability).*" • "*One must experience or knowledgeable to identify any smaller indicators which could trigger a greater change.*"

5. Discussion

This study explored the nature of possible future changes affecting the forest bioeconomy and examined how to identify and interpret weak signals of change in the forest bioeconomy operating environment. A two-stage Real-Time Delphi method was used and an international panel of experts representing the forest bioeconomy and foresight expertise was engaged. In addition to the Real-Time Delphi method, this study introduced four conceptual frameworks to use when searching for weak signals.

The results were based on the views of the panelists. The results suggest that understanding the nature of future changes affecting the forest bioeconomy operating environment is enhanced by viewing the issue through different thematic areas. When identifying possible future changes that may affect the forest bioeconomy, different strategies and policies, technology and advancements, and trends should be considered. In addition, various sources of information, such as social media, digital sources, and research articles and reports, should be considered fruitful sources where possible future changes may be identified.

According to the answers and interactions of panelists, various criteria should be considered to help identify weak signals that may affect the forest bioeconomy. Criteria include, for example, thinking outside the box and following the behaviors and views of consumers. In addition, multidisciplinary discussions and initiatives outside the traditional forest sector, for example, in social media, can be identified as possible channels for detecting weak signals.

The results imply that weak signals can be found from the same sources as future changes, but the interpretation of weak signals can be considered as difficult as what has been observed in previous weak signals studies (e.g., Lesca et al., 2012, van Veen and Ortt, 2021,). According to the present results, unlike in the case of future changes, research publications and reports are viewed as ineffective sources for identifying weak signals because of the long timeline of research and potential science-based variables. In addition, results about where to identify future changes and where to identify weak signals are parallel in many respects because they have many commonalities in their characteristics. In some cases, signs of future changes and weak signals can be identified from the same sources, but the question is not self-evident because weak signals are found much less frequently than general signs of change.

Overall, the second research question on how weak signals can be identified and interpreted was found to be challenging during the analysis. Identification and interpretation of weak signals are much more complicated than what experts may have expected in this study. Weak signals do not force themselves to be exposed as they are part of complex systems and are therefore classified as "weak" (e.g., Hiltunen, 2010; Lesca and Lesca, 2014). According to the results, this study cannot give a direct answer or guideline for the identification and interpretation of weak signals, but however can structure the thoughts of those search for and interpreting weak signals.

An example of this structure can be considered the four conceptual frameworks used in this study. The purpose was to identify the selected conceptual frameworks as exploration areas to use when searching for weak signals. This conceptual contribution connected the views of experts with the purpose of the study, aiming to investigate how to identify and interpret weak signals. However, detecting potential weak signals requires additional insight, which was not obtained in this study. For example, the collected expert views did not give an absolute "stopping rule" for detecting weak signals when observing signals of change. Therefore, further research is needed to develop a theory of weak signals detection in the forest bioeconomy.

Previous studies related to the detection of weak signals (e.g., Toivonen, 2004; Kuosa, 2010; Holopainen and Toivonen, 2012; Eckhoff et al., 2014; Mühlroth and Grottke, 2018) can be used to help to detect weak signals in the forest bioeconomy. Methods in these studies include algorithmic data mining techniques with change or outlier analyses (Kuosa, 2010; Eckhoff et al., 2014; Mühlroth and Grottke, 2018). In addition to these quantitative methods, also qualitative methods as the present Delphi approach, and the combinations of these two procedures can be seen as potential processes in which weak signal detection techniques could be experimented in further studies.

Regarding the four conceptual frameworks used in the present analysis, the results imply that future forest bioeconomy changes could appear in niche innovations or even in regime and landscape levels in the MLP model. This perspective is shared by Geels and Schot (2007), who observed that a broad landscape level could add pressure to an existing regime, causing change. In the Three Horizons Framework, new technologies and innovations in Horizon 2 could help our understanding of Horizon 3 and early signs of change in a new dominant system. This view is supported by Curry and Hodgson (2008). These findings are connected to complexity theory, where a change in a system can produce unexpected outcomes (Morel and Ramanujam, 1999). Combined with weak signals of change, possible, plausible, and preferable futures can be explored more creatively.

According to our results, the MLP model could also be used as a conceptual framework when searching for weak signals of change. In addition, with the help of MLP model, it is possible to interpret potential wild cards as weak signals. Innovations tend to break into operating models, for example, when the operating environment and system act as drivers, a view supported by Geels and Schot (2007). As with future changes, forerunners of new ideologies in Horizon 2 could aid in understanding Horizon 3 and early signs and weak signals of a new dominant system (Curry and Hodgson, 2008).

According to our results and Geels and Schot (2007), interpreting weak signals is challenging, but the MLP could be used to describe changes in history retrospectively. In addition, in the case of the forest bioeconomy, the interpretation through the operating environment is supported by "outside-in thinking", i.e., pondering how external changes could profoundly affect a given field or domain eventually (Scearce et al., 2004). However, the results obtained with the help of the four conceptual frameworks have limitations. For example, the experts had opportunities to bring ideas that were connected to complexity theory, but they did not bring these issues to the fore. This may indicate that the topic of how to identify and interpret weak signals is difficult for experts to answer ad hoc in an online questionnaire; therefore, in follow-up studies and practical applications, futures literacy with common conceptual knowledge needs to be developed with some initial training and communication among forest experts before entering weak signal exploration campaigns.

In addition, due to the conceptual approach of this study, follow-up studies need to identify information more effectively about the channels from which weak signals can be identified. According to the experiences gathered from this study, interaction and cooperation can be considered key aspects when searching for weak signals in follow-up studies. Interaction and cooperation are also needed in the above-mentioned initial training and communication phases. This is particularly important among forest professionals, as searching for weak signals can be especially challenging without preliminary knowledge of future studies and initial information about weak signals.

Interaction and discussion played a key role in the data collection of this study. In the expert matrices, diverse stakeholders and areas of expertise were chosen based on the idea that different perspectives would be obtained on the research questions. For this reason, an international panel was recruited, with the aim of gathering diverse insights into how to identify and interpret weak signals. While the number of participants in the panel was not high, the overall expertise represented different types of forest bioeconomy organizations, different places in value chains, and various types of futures expertise. We find this sufficient for this exploratory study. However, consistent with the Delphi method, answers, and comments were anonymous to both the participants and the researchers who conducted the study. For this reason, more detailed analysis of the participant groups was limited, which can however be considered a merit of this study.

In the expert matrices (Tables 1 & 2), the goal was to obtain sufficient information from the experts on the subject under investigation. Another goal was for the insights of futures and foresight specialists to help forest bioeconomy experts answer future-oriented questions more creatively. These goals were reached. However, the professional backgrounds of the participants may have affected the results in understanding future changes and weak signals. Futures research and foresight specialists bring a holistic or systems perspective to examine the forest bioeconomy, and they view and understand future changes and weak signals with wider lenses.

In addition, the different temperament traits of the actors could affect how weak signals can be identified and interpreted. The genetics of human temperaments have been studied in the field of psychology (e.g., Cloninger et al., 2019; Zwir et al., 2020). In futures research, the Myers Briggs Type Indicator (MBTI) has been used to help understand the future orientation of actors (e.g., Morrow, 2005; Voros, 2018). Different actors perceive and react to a novel situation differently. Therefore, follow-up studies that search for weak signals interactively or cooperatively should including diverse group of personality types and include participants who have a range of attitudes towards the future.

This study primarily examined experts' views on the nature of future changes and weak signals. This does not mean that the present experts provided all relevant information on what the future changes are and how to identify and interpret weak signals. Therefore, the results should be seen as perceptions of various experts rather than as objective truth. The expert-based Real-Time Delphi method as a foresight instrument in this study produced initial results and not the final word. However, that was to be expected, as there are no facts about the future (Bell, 1996, 1997), and the nature of the topic is such that qualitative futures research will always produce subjective perceptions rather than objective truth. However, with the help of the participants' views, it was possible to gain insights into what the nature of future changes and weak signals could be in the future forest bioeconomy and how to start identifying and interpreting them.

6. Conclusions

This study has contributed to development of the theory and practice of identifying and interpreting weak signals of change in the forest bioeconomy. The Real-Time Delphi method was shown to be a useful expert-based method for collecting views on how to identify and interpret weak signals. Although this study does not provide absolute guidelines for identifying and interpreting weak signals, the four conceptual frameworks help structure thinking and provide general guidelines.

This exploratory study provided an understanding of the conventional procedures for identifying and interpreting weak signals in the forest bioeconomy operating environment. Therefore, in follow-up studies, the focus should be on how conventional procedures for identifying weak signals should be refined and improved so that weak signals could be identified more efficiently and effectively. The four conceptual frameworks used in this study structured the theoretical understanding of how to identify and interpret weak signals. Subsequent studies should focus on more practical aspects such as how to select diverse group of experts to participate in the search for weak signals.

Due to the tentative nature of the results, it is important to understand the contribution of this research to forest science. This study has shown that expert-based data about how to identify and interpret weak signals in the forest bioeconomy have strengths and weaknesses. For example, the data suggest that an understanding of the future of the forest bioeconomy, especially weak signals of future changes, needs to be strengthened among forest bioeconomy experts. Collaboration and interaction between futures specialists and forest bioeconomy experts could broaden the view of scanning for weak signals of forest bioeconomy in the future. Interaction and cooperation are also needed in the training and education phases before the actual search for weak signals. This is particularly important in fields such as forestry where weak signals have not been studied extensively.

The results of this study indicate that further research on weak signals detection in the forest bioeconomy is needed. Developing foresight and futures understanding is important in forest sciences to examine discontinuities, such as shocks and weak signals, more effectively and efficiently. In operating environment analysis, it is important to look at the impact of trends and megatrends and to be aware of weak signals of change. An awareness of weak signals can help decision makers build preparedness and resilience for changes that may be critical in the forest bioeconomy operating environment in the future.

CRediT authorship contribution statement

Tuomas Mauno: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Fellice Catelo:** Conceptualization, Methodology, Formal analysis, Visualization, Writing – review & editing. **David N. Bengston:** Conceptualization, Methodology, Writing – review & editing. **Jouni Pykäläinen:** Conceptualization, Methodology, Writing – review & editing. **Teppo Hujala:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

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

Data availability

Collected data to this article (completed and anonymized Real-Time Delphi stages) can be found online at https://doi.org/10.5281/zenodo.8402507.

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Appendix A. eDelphi first stage questions

Question 1/6: Signs of future changes in general

First, let's start with the concept of change on a general level. By considering that various types of changes are and will be happening in the world, how to identify any upcoming change.

Question 1: What criteria could be used for identifying possible future changes? What kind of signs or signals of change would capture your attention when exploring information?

Question 2/6: Signs of future changes affecting the future forest bioeconomy

Think what the previous question means in the case of the broad environment in which the forest bioeconomy operates. In considering possible future changes, how would you identify any upcoming change that may have an impact on the forest bioeconomy.

Question 2: What criteria could be used for identifying possible future changes that may affect the forest bioeconomy?

Question 3/6: Sources of future changes in general

Let's move closer to searching for future changes. Future changes and the present can have a connection. From which sources could one get useful information that leads to identification of future changes?

Question 3: Where do the possible future changes appear in the present? What are some channels, platforms, or sources of information where possible future changes may be identified?

Question 4/6: Sources of future changes affecting the future forest bioeconomy

After contemplating the different sources where future changes may generally be identified, now think about the forest bioeconomy. From which sources could one get information that leads to identification of changes that may affect the forest bioeconomy?

Question 4: Where do the possible future changes that may affect the forest bioeconomy appear in the present? What are some channels, platforms, or sources of information where those possible future changes may be identified?

Question 5/6: Features and characteristics of future changes in general

Now that you have elaborated the information sources for identifying possible future changes, let's conceptualize the future changes. What is the nature of future changes in general?

Question 5: What do you think what might be some key features and characteristics of future changes?

Question 6/6: Features and characteristics of future changes affecting the future forest bioeconomy

Finally, let's consider the forest bioeconomy and its operating environment. What is the nature of future changes that may affect the forest bioeconomy?

Question 6: What features or characteristics may those possible future changes have that may influence the forest bioeconomy?

Appendix B. eDelphi second stage questions

Question 1/6: Signs of weak signals in general

Answers of the first stage question 1/6 (*What criteria could be used for identifying possible future changes? What kind of signs or signals of change would capture your attention when exploring information?*) were categorized using NVIVO qualitative data analysis software. The most referred topics and their frequencies are presented below.

	Sustainable development	Sustainability	Strategies and policies	Technology	Trends
Number of references	6	7	5	2	3

Considering this summary and other information, how can weak signals of change be identified through indicators or evidence we have in present?

Second stage Question 1: In general, what evidence or indicators could be used for identifying possible weak signals of change? What kind of signs or pieces of evidence of weak signals would capture your attention when used for identifying possible weak signals of change?

Question 2/6: Signs of weak signals affecting the future forest bioeconomy

Answers of the first stage question 2/6 (*What criteria could be used for identifying possible future changes that may affect the forest bioeconomy?*) were categorized using NVIVO qualitative data analysis software. The most referred topics and their frequencies are presented below.

	Carbon	Climate change	Forest resources	Technology	Use of forests
Number of references	4	3	3	2	8

Considering this summary and other information, how can weak signals that may affect the future forest bioeconomy be identified?

Second stage Question 2: What evidence or indicators could be used for identifying possible weak signals of change that may affect the future forest bioeconomy?

Question 3/6: Sources of weak signals in general.

Answers of the first stage question 3/6 (*Where do the possible future changes appear in the present? What are some channels, platforms, or sources of information where possible future changes may be identified?*) were categorized using NVIVO qualitative data analysis software. The most referred topics and their frequencies are presented below.

	Media	Political debate	Research	Social media	Web discussion
Number of references	7	3	4	5	2

Considering this summary and other information, what sources are likely to be useful for identification of weak signals?

Second stage Question 3: In general, where do weak signals of change appear first? What are some channels, platforms, or sources of information where weak signals of change can be identified?

Question 4/6: Sources of weak signals affecting the future forest bioeconomy.

Answers of the first stage question 4/6 (*Where do the possible future changes that may affect the forest bioeconomy appear in the present? What are some channels, platforms, or sources of information where those possible future changes may be identified?*) were categorized using NVIVO qualitative data analysis software. The most referred topics and their frequencies are presented below.

	Climate change	EU commission	History and past development	Same answers as in question 3/6	Technology
Number of references	2	2	2	5	2

Considering this summary and other information, what sources are likely to be useful for identification of weak signals that may affect the future forest bioeconomy?

Second stage Question 4: What are some channels, platforms, or sources of information where weak signals of change affecting the future forest bioeconomy can be identified?

Question 5/6: Features and characteristics of weak signals in general.

Answers of the first stage question 5/6 (*What do you think what might be some key features and characteristics of future changes?*) were categorized using NVIVO qualitative data analysis software. The most referred topics and their frequencies are presented below.

	Bioeconomy	Climate change	Cross-sectoral	Diversity	Sustainability
Number of references	5	3	2	2	3

Considering this summary and other information, what is the nature of weak signals in general?

Second stage Question 5: What do you think what might be some key features and characteristics of weak signals in general? (not forest specific).

Question 6/6: Features and characteristics of weak signals affecting the future forest bioeconomy.

Answers of the first stage question 6/6 (*What features or characteristics may those possible future changes have that may influence the forest bioeconomy?*) were categorized using NVIVO qualitative data analysis software. The most referred topics and their frequencies are presented below.

	Climate change	Energy	European Union	Use of forests	Sustainability
Number of references	3	2	3	5	3

Considering this summary and other information, what is the nature of weak signals that may affect the future forest bioeconomy?

Second stage Question 6: What are the features or characteristics of possible weak signals of change that may influence the future forest bioeconomy?

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