



## ARTICLE OPEN ACCESS

# A Novel Method to Infer Harbor Porpoise Foraging Behavior From Acoustic Data: A Comparative Assessment Against Established Techniques

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## ABSTRACT

Assessing foraging behavior of harbor porpoise (*Phocoena phocoena*) from acoustic data has become increasingly common. Yet, a wide range of analytical methods is currently used, often without formal evaluation of their comparability. This lack of cross-method validation limits the ability to compare findings across studies and interpret differences in reported foraging activity. This study addressed this challenge by providing a systematic comparative evaluation of acoustic foraging detection methods, while introducing a novel refinement, the Search Buzz Foraging Identification (SBFI) method. We aimed to quantify the degree of similarity of the SBFI method alongside four established methods that use acoustic data and more specifically inter-click intervals to identify foraging behavior. All methodologies were applied to the same F-POD dataset collected at two locations for a full year. Comparability among methods was evaluated using correlation, distance, and trend analyses to assess agreement in relative patterns, absolute magnitude, and temporal dynamics. Most methods indicated strong agreement in relative foraging patterns and temporal trends; however, differences in magnitude and context-dependent biases emerged under specific spatial or seasonal conditions, suggesting methods are not completely interchangeable. The SBFI method showed strong correlation with several existing methods while providing a comprehensive and accessible framework for identifying foraging behavior. This study gives a systemic overview of existing foraging metrics and provides a basis for improved comparability and interpretation of acoustic-based foraging studies.

## 1 | Introduction

The harbor porpoise, *Phocoena phocoena*, is a small cetacean with a wide distribution in and around European waters (Hammond et al. 2002, 2013; Reid et al. 2003). They use echolocation to navigate, forage, and communicate by emitting narrow-band high-frequency (NBHF) clicks (Sørensen et al. 2018). These can be single clicks or grouped in so-called click trains (Koschinski

et al. 2008; Schaffeld et al. 2016; Teilmann et al. 2002; Verboom and Kastelein 1997; Verfuß et al. 2009).

As harbor porpoises have a high energy demand and high metabolism due to their small body size (MacLeod et al. 2007; Wisniewska et al. 2016), understanding their foraging behavior is vital to inform conservation strategies, understand, and mitigate human impacts (Booth 2020; Wisniewska et al. 2016).

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Despite its ecological significance as a marine top predator and its status as a strictly protected species in the EU (92/43/EEC Annex IV), many gaps remain in our understanding of harbor porpoise foraging behavior and its drivers. Current research is often constrained by methodological or technical challenges (Mann 1999), such as difficulties in observing foraging behavior in the wild due to the nature of harbor porpoises and the limitations of existing tracking and recording technologies (DeRuiter et al. 2009). To overcome these challenges, several studies have developed methods aiming at the identification of foraging behavior using tags (DeRuiter et al. 2009; Wisniewska et al. 2016), visual surveys (Koschinski et al. 2008), and/or passive acoustic monitoring (PAM) (Koschinski et al. 2008; Pirodda et al. 2014).

A big aid in observing harbor porpoise and their foraging behavior has been the development of fixed autonomous recorders (AR) for PAM (Sousa-Lima 2013). These developments facilitated marine mammal monitoring for longer periods of time and in more remote areas while also being more time- and cost-effective. Moreover, the use of ARs advanced research in the sense that porpoise monitoring could happen in all weather conditions and even at night, which filled a gap visual methods couldn't close (Calonge et al. 2024; Thomsen et al. 2005). An example of those fixed AR is the cetacean logger or the automated porpoise-click-detector developed by Chelonia with T-PODs, C-PODs, and the latest model F-PODs (Chelonia Limited 2025; Tregenza 2006). These loggers are optimized to record click parameters continuously for 4 months, include basic species identification (detecting NBHF click producers such as porpoises, other cetaceans such as dolphins, and sonar), and analyze cetacean click trains and click rates through a KERN-F classifier (Chelonia Limited 2025; Thomsen et al. 2005).

Acoustic descriptions of harbor porpoise's echolocation like clicks, click trains, click rates, and click bursts have been made early on using hydrophones and tape recorders (Verboom and Kastelein 1995, 1997). Harbor porpoises only produce NBHF clicks, which are emitted in sequences known as click trains. A click train consists of consecutive single clicks and may last several seconds (Verboom and Kastelein 2003). Variation in click characteristics such as inter-click intervals (ICIs) or click rates provides important information about their vocalization behavior (Clausen et al. 2011; Verfuß et al. 2009). Click trains can serve different functions, including social communication and navigation during travel (Koschinski et al. 2008; Miller 2008; Sørensen et al. 2018). Social calls or clicks are characterized by high and variable repetition rates (Clausen et al. 2011; Sørensen et al. 2018) and fast repeated mushroom-shaped patterns where the click rate rapidly increases to a peak or plateau before decreasing again (Migneault et al. 2025). Traveling clicks are clicks emitted to investigate their environment and therefore produced with longer ICIs, allowing the animal to sample a larger area with each click (Koschinski et al. 2008; Miller 2008; Nuuttila et al. 2013). Another distinct type of these consecutive clicks within a click train is foraging buzzes (Figure 1; Miller 2008). A foraging buzz is the terminal phase of a click train where prey capture is being attempted, after the porpoise has accurately

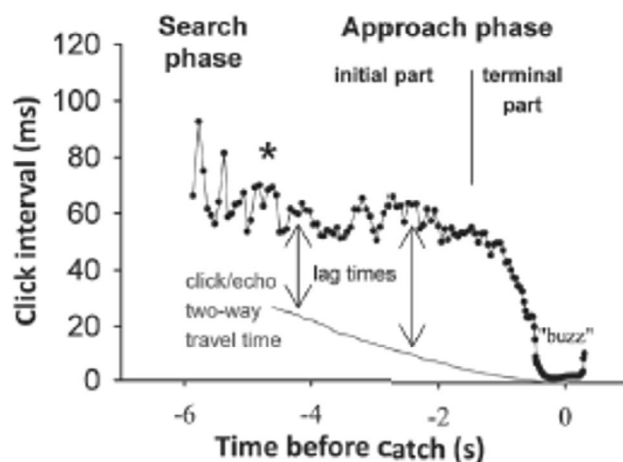


**FIGURE 1** | Click pattern from a captive harbor porpoise, taken from Miller (2008).

located their prey and quickly responded to its movements (DeRuiter et al. 2009; Koschinski et al. 2008; Miller 2008; Pirodda et al. 2014; Sørensen et al. 2018; N. Todd et al. 2022). Compared to traveling buzzes, foraging buzzes are characterized by shorter durations and shorter ICIs. Unlike the more variable ICIs observed in social calls, foraging buzz ICIs remain relatively constant even under different feeding conditions (Sørensen et al. 2018). Foraging buzzes have also been shown to continue after successful prey capture (DeRuiter et al. 2009) and have been found to be distinct in duration and repetition rate from social calls when using movement tags (Sørensen et al. 2018), though these duration boundaries can become less clear in PAM data where recorded buzzes are frequently incomplete.

In this paper, we present a refined methodological framework developed through the integration and adaptation of multiple established methods used to quantify harbor porpoise foraging behavior. The aim of this benchmark study is to present a novel, refined method to detect harbor porpoise foraging activity from acoustic data, evaluating and comparing its performance against established methods used over the past three decades.

The benchmark analysis is based on a year-long dataset (2023) from two monitoring stations, Belwind and Faulbaums, equipped with F-PODs in the Belgian part of the North Sea (BPNS) (Calonge et al. 2026). By applying different methodologies to the same dataset, we assess how methodological choices influence the identification and quantification of foraging behavior. This comparative framework allows us to explore methodological consistency, clarify differences in classification criteria, and improve transparency in foraging detection. Building on insights from previous studies, the refined SBF method aims to enhance specificity in distinguishing foraging buzzes from other click types, while maintaining comparability with earlier work. By providing an open-source and clearly defined framework, this study contributes to improving reproducibility and supporting robust ecological inference for conservation and management applications.

## 2 | Methods

### 2.1 | Established Foraging Quantification Methods

Based on a systematic literature review of studies published between 1995 and 2025 (see Table A1 for full search methodology and results), we selected four distinct, established acoustic methodologies to evaluate in our comparative analysis alongside our novel refinement (Table 1). The foraging detection methods in the comparative analysis included those of DeRuiter et al. (2009), Nuuttila et al. (2013), Pirotta et al. (2014) and Schaffeld et al. (2016). These methods have been cited and used (with small adjustments) in several of the papers retained in the literature survey. The method of Nuuttila et al. (2013) was chosen over the method of Carlström (2005) due to high similarities between the methods ( $ICI < 10$  ms), and because the paper of Nuuttila is more detailed.

Because absolute ground truth data (e.g., from animal-attached bio-logging tags such as DTAGs or direct visual observations) were unavailable for this dataset, these established methodologies were used as relative benchmarks. In the absence of an independent baseline, evaluating inter-method agreement and consistency across these established algorithms provides the most robust means to assess the performance and temporal patterns of our novel refinement.

All four methodologies were executed as closely as possible to their original published specifications, and a reproducible R script containing the code for each analysis is openly available on GitHub with a descriptive readme file (Aoufi 2026).

The methodology developed by Pirotta et al. (2014) used the click characteristics from T-PODs and C-PODs (Chelonia Limited, UK) and identified foraging buzzes using gaussian mixture models that are fitted to the natural log-transformed ICIs. The R package *mixtools* v2.0.0 (Benaglia et al. 2009) was used to characterize the distribution of ICIs and assign each ICI to one of three groups namely, (i) buzz ICI, (ii) regular ICI, or (iii) long ICI (Pirotta et al. 2014). Buzz ICIs are then summarized from click level to minute level named Buzz Positive Minutes (BPMs). BPMs, summarized per hour, were modeled as response variable for the analysis.

Similarly, Nuuttila et al. (2013) used click characteristics of C-PODs (Chelonia Limited, UK) to define foraging buzzes. Here, ICIs with a value larger than 250 ms were considered outliers

and removed before the analysis. Feeding buzzes were defined as having at least one ICI below 10 ms within a click train, this in accordance with Carlström (2005) and Wisniewska et al. (2012).

Research of DeRuiter et al. (2009) made use of a modified Dtag to study foraging behavior. A foraging buzz was defined as the time period during which the click rate exceeds 125 clicks/s ( $ICI < 8$  ms) and ends when the click rate falls below this threshold.

Schaffeld et al. (2016) considered 10-min time bins to identify foraging behavior. A porpoise-positive 10-min period (pp10min) was classified as a foraging period (fpp10min) if it met two conditions. First, the 10-min sequence should contain at least five clicks with an ICI below 10 ms. Second, the sequence should include a sudden decrease in ICI, where the interval dropped to at least two-thirds of its initial value to below 10 ms (Schaffeld et al. 2016).

### 2.2 | The Novel SBFI Method

We developed an adjusted method which is a combination of the results from Sørensen et al. (2018), DeRuiter et al. (2009), Pirotta et al. (2014), and Miller (2008) that aims to partially avoids social calls, for comparison with the earlier mentioned approaches. Our method considered individuals clicks rather than a click train as the directionality of harbor porpoise echolocation could lead to a loss of some clicks and thus potentially interrupted and poorly defined trains (Berges et al. 2019). DeRuiter et al. (2009), Pirotta et al. (2014), and Sørensen et al. (2018) found an average foraging buzz ICI around 3–3.5 ms (321 clicks/s). Furthermore, buzz click rates for harbor porpoise are said to be several 100 to about 700 clicks/s (Akamatsu et al. 2007; DeRuiter et al. 2009; Miller 2008; Verboom and Kastelein 2003; Verfuß et al. 2009). Sørensen et al. (2018) found that social calls are distinct from foraging buzzes in both repetition rate and duration with the mean ICI of foraging buzzes remaining relatively constant despite different feeding conditions. Additionally, foraging buzz clicks had a different peak in ICIs ( $\approx 2.25$  ms, visually projected from Figure 2) compared to social call clicks ( $\approx 1.1$  ms and  $\approx 7.1$  ms, visually projected from Figure 2) (Sørensen et al. 2018). Based on this information and the improved detection and sensitivity of an F-POD compared to a C-POD (Ransijn et al. 2024; N. Todd et al. 2023), an adjusted and stricter method aimed to distinguish between foraging buzzes and the majority of

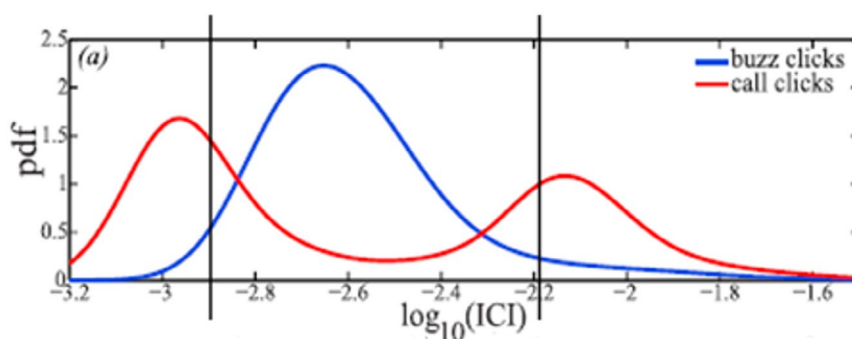


**FIGURE 2** | Power density function (pdf) of inter-click intervals (ICIs) separated into foraging buzz clicks and social call clicks, taken and adjusted from Sørensen et al. (2018) by adding our SBFI boundaries.

social calls was created, namely the “SBFI” method. This by defining a foraging buzz as having at least three consecutive ICIs between 1.25 ms ( $\pm 800$  clicks/s) and 6.65 ms ( $\pm 150$  clicks/s) and to define a foraging positive minute, a search or approach phase click needs to be present within the same minute which is defined as having a click with a click rate below 200 clicks/s before this foraging buzz to avoid classifying repeated buzzes as foraging (Migneault et al. 2025; Miller 2008). As there could be multiple porpoises foraging and buzzes are known to continue after potential prey capture, if multiple buzz sequences occurred within the same minute, each buzz sequence was evaluated independently and the minute was

classified as foraging if any buzz sequence satisfied both criteria (Figure A1).

2.3 | Data Collection

To test the reviewed methodologies against our proposed SBFI method, 1 year of open F-POD data was sourced from the Cetacean passive acoustic network (Flanders Marine Institute (VLIZ), Belgium 2021) in the BPNS (Calonge et al. 2024) for the whole of 2023 except for a small 3-week gap during June where no tripods were deployed (Figure 3). The BPNS

TABLE 1 | Comparative summary of the five foraging behavior methodologies evaluated.

| Methodology             | Analysis type | Approach                             | Key criteria                                                                                                                      |
|-------------------------|---------------|--------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| DeRuiter et al. (2009)  | Click-based   | Deterministic                        | Buzz begins when click rate > 125 clicks/s (ICI < 8 ms) and ends when it drops below.                                             |
| Nuuttila et al. (2013)  | Train-based   | Deterministic                        | ICI > 250 ms discarded; requires at least 1 ICI < 10 ms within a defined click train.                                             |
| Pirotta et al. (2014)   | Click-based   | Statistical (Gaussian mixture model) | Normal log-transformed ICIs categorized into 3 clusters of which one buzz ICI cluster                                             |
| SBFI (this study)       | Click-based   | Deterministic                        | Requires $\geq 3$ consecutive ICIs between 1.25–6.65 ms, preceded in the same minute by a search/approach click (< 200 clicks/s). |
| Schaffeld et al. (2016) | Train-based   | Deterministic                        | Requires $\geq 5$ clicks with ICI < 10 ms AND a sudden ICI drop of 2/3 from initial value to < 10 ms within the 10 min bin.       |

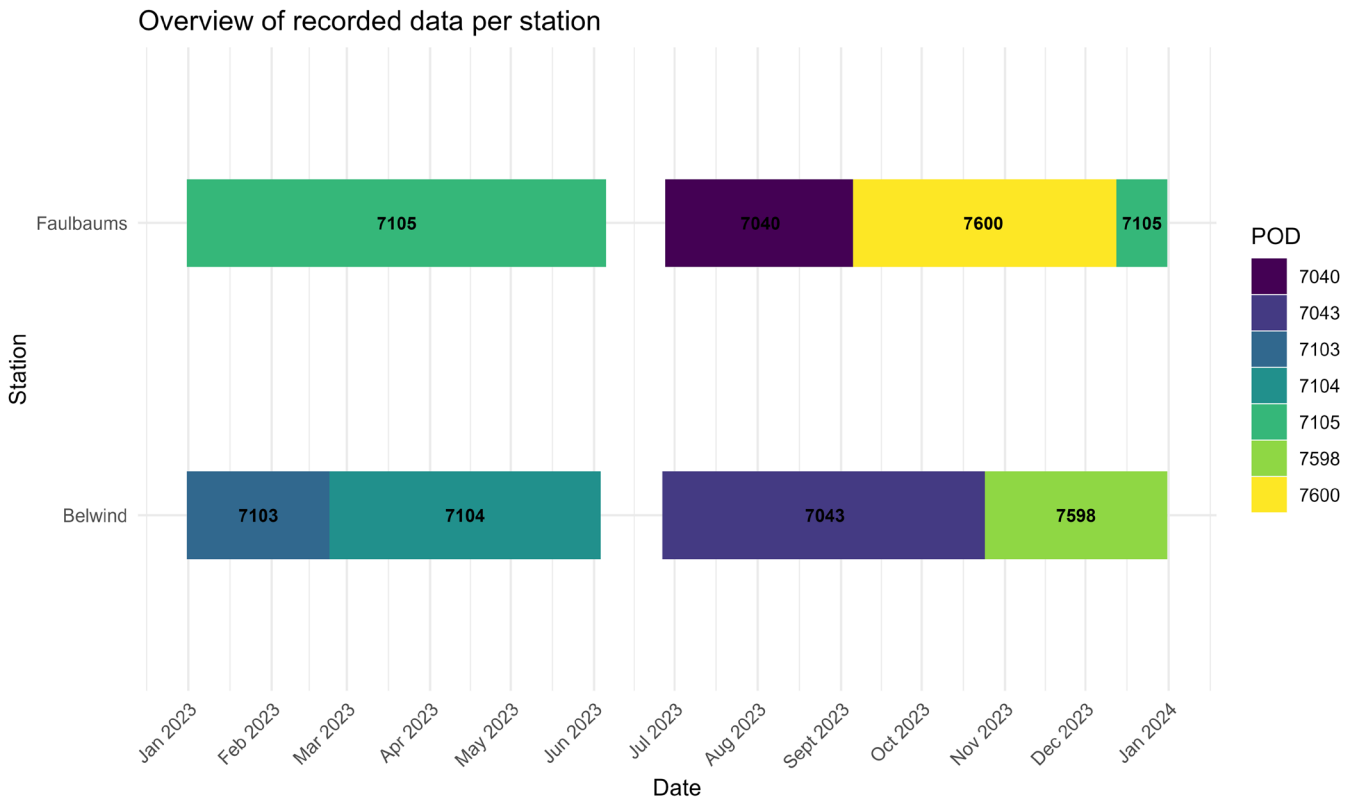


FIGURE 3 | Total recording period of all F-PODs combined for both locations in 2023. Note a gap of 3 weeks in June when no tripods were deployed in either station.

is characterized by a sandbank system, high currents, and a max depth of 40 m. All acoustic data and metadata used in this study are publicly archived and accessible to ensure full scientific reproducibility. The underwater acoustics component of ETN hosts all metadata and detection positive minute (DPM) data of C-PODs and F-PODs in minute resolution, and IMIS hosts the data containing the inter click intervals used in this study (Calonge et al. 2026). DPMs and ICIs for NBHFs species for the whole detection period were exported directly using the built-in export routines in the Chelonia F-POD application version January 25, 2024, from raw FP1/FP3 data files, retaining only detections classified as high and moderate quality. The F-PODs are moored on the seafloor using a tripod structure as described in Calonge et al. (2024). Two stations were selected to evaluate whether methodological outputs remain consistent under contrasting environmental conditions, one located within the offshore wind farm Belwind (depth 23 m) and one situated mid-shore near the shipping lane and adjacent to shipwreck SS Sigurd Faulbaums (depth 25 m) (Figure 4). These stations represent distinct acoustic and habitat contexts, including differences in anthropogenic noise exposure, habitat structure, and potential prey aggregation effects associated with artificial structures. By applying the compared methods to data from both locations, we assessed whether methodological performance remained stable across varying

environmental conditions. As the classification framework is intended to be location-independent, consistency in outputs between stations would indicate robustness of the approach. A total of 350 recording days were available for each station in this study.

## 2.4 | Data Analysis

All statistical analyses and reproduction of the methods have been conducted in Rstudio (Posit team 2023) and R version 4.3.1. (R Core Team 2023) with the script available in GitHub (Aoufi 2026). Basic data exploration and tests were conducted on the presence data to check for temporal patterns. We looked at DPM rate calculated as DPM/recorded minutes (within the hour) \* 100. This to get a better picture of the absolute time porpoises were vocalizing (proxy for presence). DPM rate was checked against season and month, using R packages *hydroTSM* (Zambrano-Bigiarini 2024). The seasons were defined using the meteorological seasons: winter running from December until February, spring from March until May, summer from June until August, and autumn from September until November. Kruskal-Wallis rank sum test was used to evaluate differences in porpoise detection rates among season–location combinations, with the interaction between season and station treated

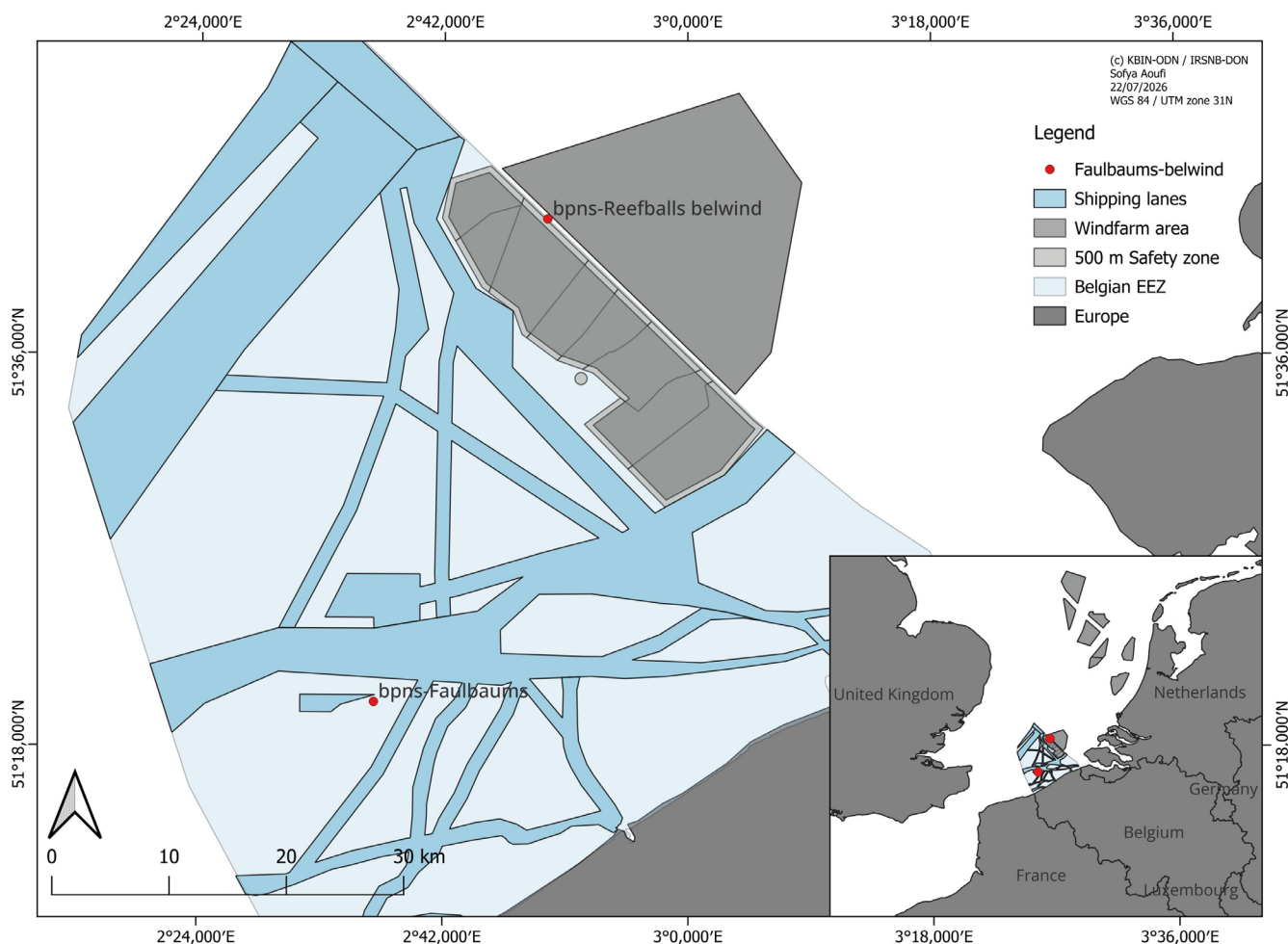


**FIGURE 4** | Overview map of the two stations of the LifeWatch Permanent Cetacean passive acoustic network in the Belgian part of the North Sea.

as a single grouping factor (eight levels). An additional Kruskal–Wallis test was performed to assess overall differences between locations. Post hoc pairwise comparisons were conducted using Dunn's test using R package *FSA*.

Feeding buzzes were calculated in R according to the five methodologies outlined in Sections 2.1 and 2.2 and aggregated by hour for each location. To quantify foraging behavior, two metrics were used: (1) the absolute amount of time porpoises spent foraging, measured as BPMs aggregated by hour; (2) and a proportional measure of foraging time (foraging rate), calculated as the time spent foraging (BPM) in each hour divided by the total time the porpoise was detected as present (DPM) in that same hour mentioned as BPMrate. To enable a direct comparison with the method proposed by Schaffeld et al. (2016), buzz clicks from the other methods were also aggregated into BP10M (buzz positive 10-min) intervals and BP10Mrate (Buzz positive 10-min per hour divided by the DP10M per hour).

While the absolute duration of foraging time provides a straightforward count of how many minutes porpoises were engaged in foraging, this measure can be misleading if not considered in relation to their overall presence. For example, a porpoise that foraged for 2 min over a 1-h period may appear to be largely non-foraging. However, if the porpoise was only present (i.e., detected) for 2 min in total, it was in fact foraging 100% of the time it was present. By dividing foraging time by presence, the proportional measure controls for variation in detectability, allowing for a more accurate comparison across time periods. This ratio therefore offers a clearer insight into their behavioral choices when present.

To assess differences in porpoise foraging rates among season–location combinations for each methodology, a Kruskal–Wallis rank sum test was used. An additional Kruskal–Wallis test was performed to assess overall differences between locations. Post hoc pairwise comparisons were conducted using Dunn's test to identify which season differed from each other for each method using R package *FSA* (Ogle et al. 2023).

To test the agreement between the different methods, a correlation analysis, a distance analysis, and a trend analysis were performed on the BPM rate and BP10M rate. A correlation analysis assessed how similar the methods behave over time regardless of their absolute values. To test for pattern or shape similarity between methods, a correlation matrix was conducted and visualized using the *cor* function from the *stats* package (R Core Team 2023) and the *corrplot* package (Taiyun and Viliam 2024), comparing BP(10)M rate values from each method with those from the other methods at each location. A Pearson correlation coefficient was used as the relationships between the data generated by the different methods were highly linear.

The distance and trend analysis informs us on the magnitude and stability of the differences between methods, giving insights on how similar they quantify BP(10)M rate values over time. For each method pair, the average distance (bias), the variability of the distance (standard deviation/consistency), and the trend in distance over time (stability) were calculated. The distance analysis quantifies how far apart the two methods are at each

datetime by computing the difference in distance between the BPM estimates of each method pair using the *dist* function from the *base* R package. By calculating the standard deviation for each method pair, we gain insight into how much this distance fluctuates over time or how consistent the mean difference is. The trend analysis is performed by fitting a regression line through the pairwise differences using distance as a function over time. This slope and its corresponding significance value indicate whether the methods diverge or converge over time. A slope close to zero means the difference is stable, while a positive or negative slope signals a growing gap or reduction between methods. The *p*-value shows whether this trend is statistically meaningful.

## 3 | Results

### 3.1 | Patterns in Harbor Porpoise Presence

Harbor porpoises were detected at least once a day in either of the two locations, and were present 39.85% of the hours recorded. A Kruskal–Wallis test revealed a significant difference in detection rates among the season–location combinations (*p*-value < 2.2e-16). In addition, a significant overall difference between locations was detected (*p*-value 0.0251), indicating that detection rates differed between locations irrespective of season.

Post hoc Dunn tests showed that most season–station combinations differed significantly from one another (*p* < 0.05). However, no significant difference was found between autumn and summer at either station (Belwind: *p* = 0.3659; Faulbaums: *p* = 0.2043). Furthermore, winter and spring did not differ significantly at Belwind (*p* = 0.3310).

These results are reflected in Figure 5. Detection rates were generally highest during winter and spring and reduced during summer and autumn. Different patterns emerged in the mid-shore shipwreck location Faulbaums which revealed a broader and more pronounced peak in detections from January to April encompassing winter and early spring, as well as a smaller, secondary peak between August and October. At Belwind, detections peaked in December and March and were lowest during summer and autumn. Overall, detections were higher at Faulbaums, particularly during winter.

### 3.2 | Patterns in Harbor Porpoise Foraging Behavior

Harbor porpoise foraging buzzes were found in 92.8%–97.4% of the days when harbor porpoises were vocalizing depending on the methodology applied. The average buzz ICI length varied between 2.12 and 3.33 ms (Table 2). Schaffeld's method is generally harder to compare as it makes use of a sudden decrease condition that needs to be fulfilled in a sequence of clicks within a 10-min time interval to define foraging, leading to no clear buzz ICI length; but as it is based on ICI < 10 ms such as Nuuttila, the average buzz ICI should be similar. Important to note here is that a foraging buzz refers to a foraging attempt; this gives in no way a picture of how successful the foraging activity has been.

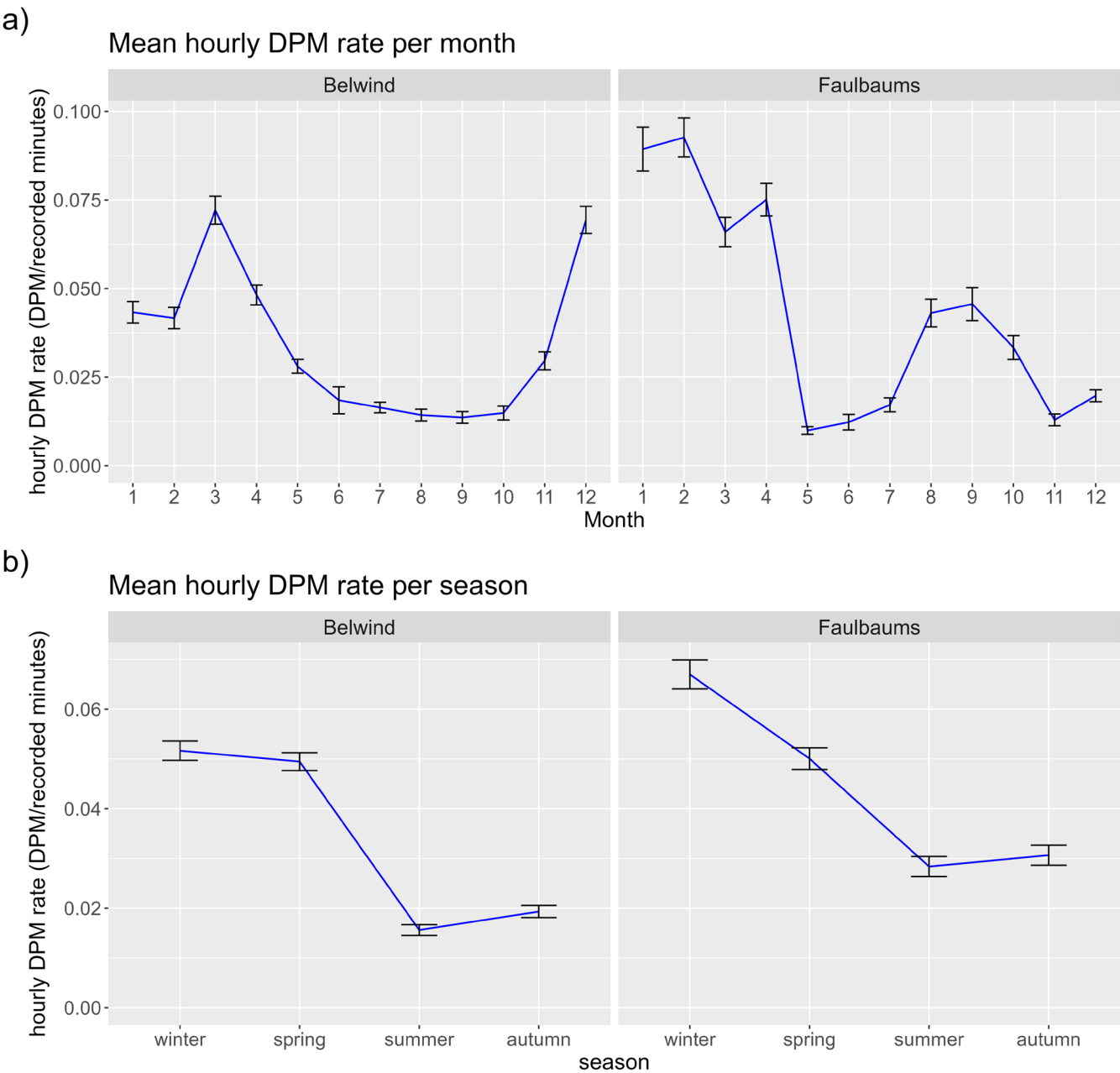


**FIGURE 5** | Mean hourly rate of Detection positive minutes (DPM/recorded minutes) per month and season with standard error for both locations. Winter (December–February), spring (March–May), summer (June–August), autumn (September–November).

**TABLE 2** | Comparison of results using different foraging detection methods for identifying foraging behavior and buzz ICIs.

| Method    | Hourly records with foraging/<br>buzz identified | Total hourly records | % of records identified<br>as foraging attempt | Average buzz<br>ICI (ms) |
|-----------|--------------------------------------------------|----------------------|------------------------------------------------|--------------------------|
| DeRuiter  | 4123                                             | 6478                 | 63.65                                          | 2.98                     |
| Nuuttila  | 4310                                             | 6477                 | 66.54                                          | 3.33                     |
| Pirotta   | 3507                                             | 6478                 | 54.14                                          | 2.13                     |
| SBFi      | 3322                                             | 6478                 | 51.28                                          | 2.77                     |
| Schaffeld | 3760                                             | 6478                 | 58.04                                          | /                        |

The two locations showed very different seasonal and monthly patterns in foraging behavior looking at BP10M rate (BP10M/DP10M per hour) (Figure 6). A nonparametric Kruskal–Wallis test indicated significant differences between both locations for all methods ( $p$ -value = 3.429e-16). In Belwind (Figure 6a), there was significantly more foraging during spring ( $p$ -values < 0.05), except for the SBFi method where spring was only significantly higher compared to winter and summer ( $p$ -values 0.00006 and 0.00572). In Faulbaums, the seasonal pattern is less pronounced except for Pirotta's method in summer where the BP10M rate is much lower ( $p$ -value < 0.00006) (Figure 6b). The monthly patterns revealed minor differences and follow the same general trend. However, it is important to note that Figure 3 indicates that only the first and the last days of June are present while the rest is missing, thus the transition from May to June and June to

July that revealed a decrease in BP10M rates for some methods and an increase for others is not reliable.

In general, the BP10M rates per hour generated using the SBFi method are more conservative than Nuuttila's and DeRuiter's but more similar in magnitude to Pirotta in Belwind while it is closer to Schaffeld in Faulbaums with some small differences between methods and locations. When comparing only the shape of the seasonal patterns, independent of magnitude, DeRuiter and Nuuttila almost follow the same temporal trend in both locations. Pirotta's method attributes the lowest relative foraging activity to summer in both locations. In contrast, our method attributes the greatest relative foraging activity to winter and autumn and the least in spring compared to the other methods' estimates.

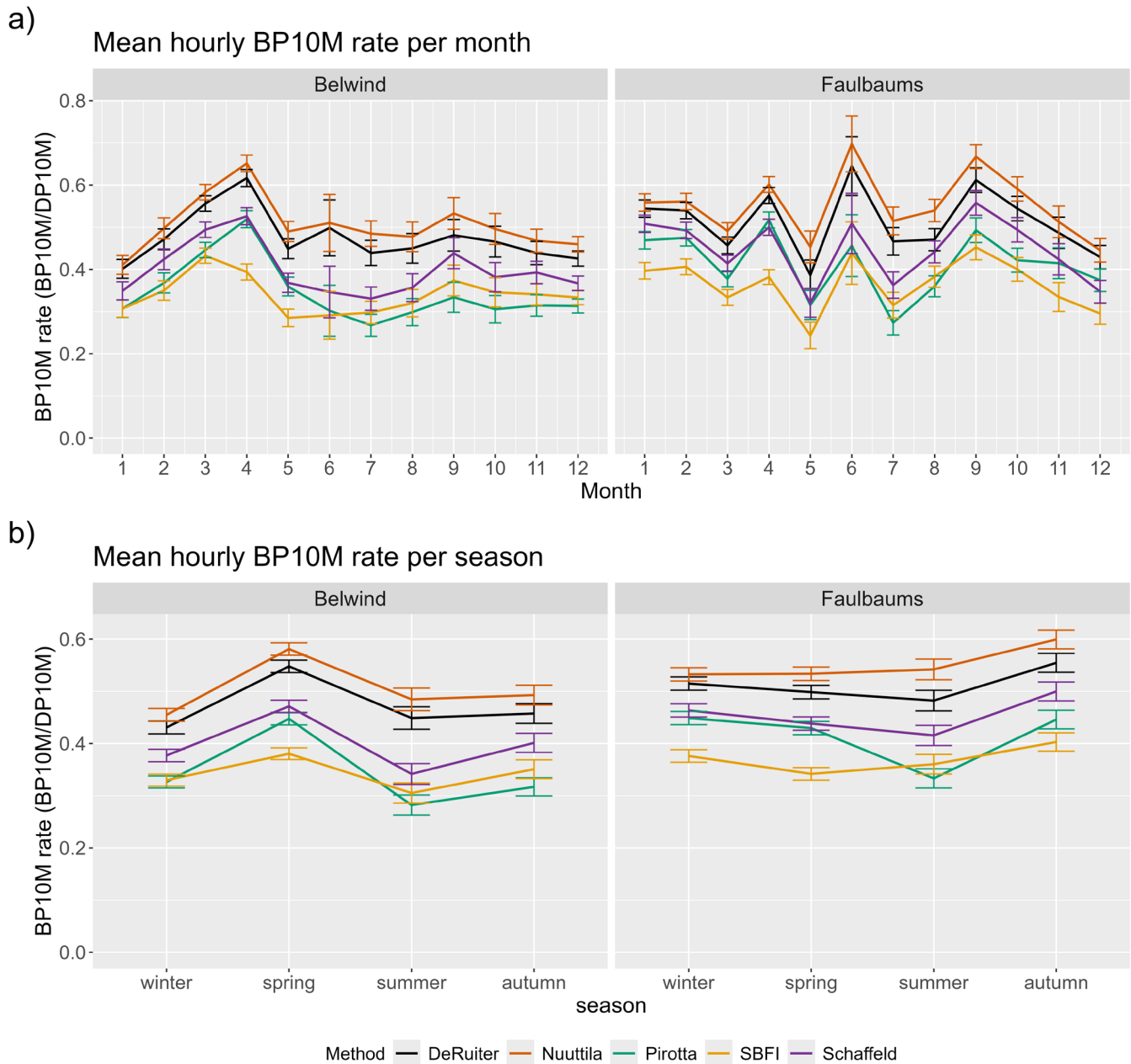


**FIGURE 6** | Mean hourly buzz positive 10-minute interval (BP10M) rate per month and season with standard error for each method and both locations. Winter (December–February), spring (March–May), summer (June–August), and autumn (September–November).

### 3.3 | Correlation Analysis, Distance, and Trend Analysis

The correlation matrices revealed substantial differences in the degree of association among the five hourly BP10M rate calculation methods (Figure 7a,b). Across both locations, correlation coefficients ranged from 0.59 to 0.95 (Figure 7), suggesting moderate to very strong correlation or similarity in patterns between methods. However, BP10M rate correlations in Belwind are lower and more variable (0.67–0.95), compared to Faulbaums (0.7–0.93). The SBFI method has a strong correlation with DeRuiter and Schaffeld (ranging from 0.76 to 0.79) over both locations. Because the SBFI method applies stricter click boundaries to exclude potential social calls, it showed the lowest overall correlation with the other methods. In contrast, the methods from Nuuttila and DeRuiter show the highest degree of association, overlapping almost completely in shape for both locations.

The BPM rate correlation plots (Figure 7c,d) indicated the lowest correlation between our SBFI method and Pirotta for both locations (0.59, 0.62). DeRuiter and Nuuttila still revealed the strongest association (0.94, 0.93), with all other correlations between methods being strong to moderate.

Figure 8 shows the mean differences (bias) between all method pairs for BP10M rate and BPM rate for both locations across the

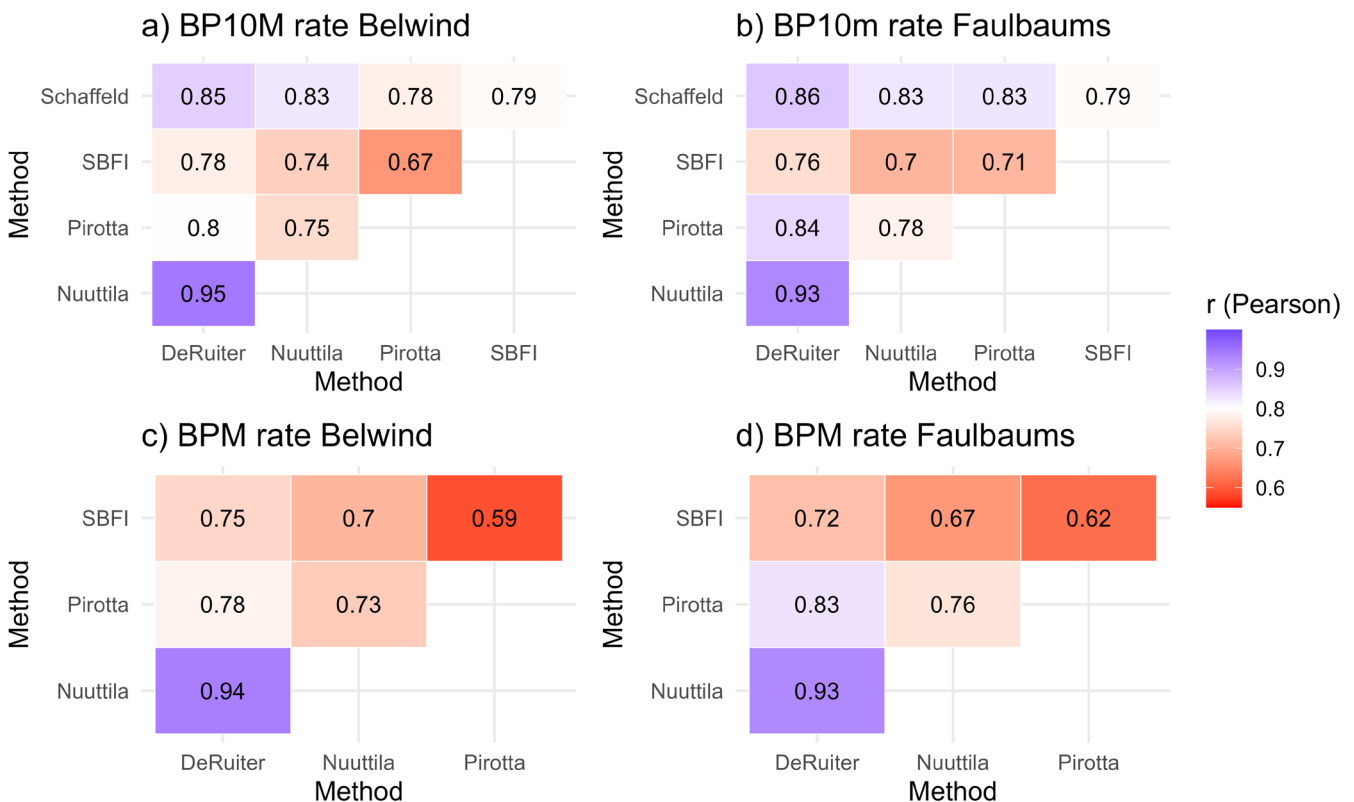
full year, together with the corresponding standard deviation and the overall trend (slope) with significance.

The standard deviation gives an indication of the temporal stability of the bias from hour-to-hour, with BP10M rates standard deviation values ranging from 0.142 to 0.328 (Tables A2 and A3). These moderate to high values suggest that, despite generally small to moderate mean differences between methods, short-term fluctuations around the bias are common.

Overall, method pair DeRuiter (1) and Nuuttila (2) (Figure 8a–d) shows a small mean bias, a moderate standard deviation, and a slope close to zero, indicating good agreement and stability. Whereas method pair Pirotta (3) and SBFI (4) has the smallest mean difference in Belwind but has a very large standard deviation, suggesting that while they show good agreement, their differences fluctuate strongly from hour to hour. In Faulbaums (Figure 8b), method pairs show smaller mean biases and standard deviations compared to Belwind, indicating greater stability between methods and more closely aligned BP10M rate estimates between methods.

For BPM rates (Figure 8c,d), all method pairs displayed small to moderate mean bias (0.021–0.171) with moderate to high standard deviations (0.126–0.267) indicating consistent hour-to-hour fluctuations (Tables A4 and A5). Method pair Nuuttila (2) and SBFI (4) has the largest mean bias, with Nuuttila consistently

### Correlation between BP(10)M rate methods



# Agreement and Temporal Stability Between BP(10)M Rate Methods

Comparison of method-pair mean bias  $\pm$  SD, trend slope, and p-value

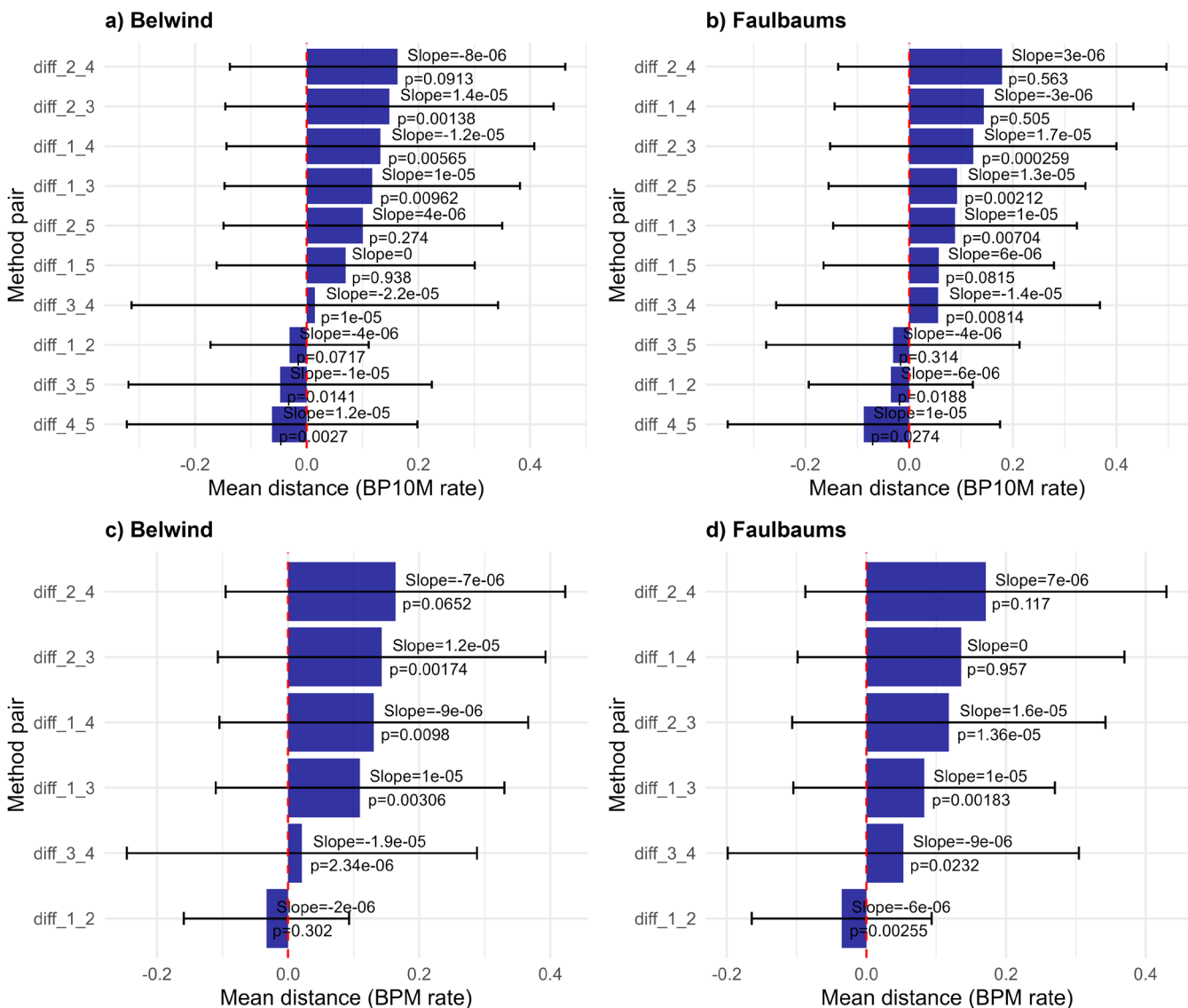


**FIGURE 8** | Distance and trend analysis, indicating mean bias  $\pm$  standard deviation, slope and respective  $p$ -value indicating trend for each location. (a, b) Ten pairwise comparisons across all five methods for the buzz positive 10-minute interval (BP10M) rate; (c, d) only six pairwise comparisons for the BPM rate because the Schaffeld method (Method 5) is excluded from the per minute analysis. Y-axis methods numbers are alphabetically 1—DeRuiter, 2—Nuutila, 3—Pirota, 4—SBFI, and 5—Schaffeld.

estimating higher BPM rate values with a fairly large standard deviation (0.259).

Generally, the agreement patterns between methods are consistent across the two locations, with the method pair with the highest agreement being DeRuiter (1) and Nuutila (2) and the worst being Nuutila (2) and SBFI (4). Pairs including Pirota (3) or SBFI (4) also seem to contribute to higher instability or fluctuations over time.

Trend analysis (slope and  $p$ -value in Figure 8) indicates that several method pairs show a statistically significant but very small increases or decreases over time (slope  $< 0.00002$  BP(10)M rate/year), suggesting that any temporal changes in method differences are negligible.

## 4 | Discussion

### 4.1 | Assessment of the Comparability of Different Foraging Detection Methods

This study introduced the novel SBFI method and evaluated its performance within the first quantitative framework comparing five harbor porpoise foraging detection methods (DeRuiter et al. 2009; Nuutila et al. 2013; Pirota et al. 2014; Schaffeld et al. 2016 and SBFI method). Using a full year of continuous acoustic monitoring data from two distinct locations in the BPNS, we systematically compared the methods against each other to evaluate their similarity in shape, magnitude and temporal and spatial patterns under pronounced seasonal variation.

Overall, our findings revealed on average high to moderate positive correlations between BP10M rates across all methods tested over a full year at two locations. Correlations among existing methods were generally high (up to  $r=0.95$ ), indicating a high degree of agreement in the temporal patterns of detected foraging activity. The SBFI method showed moderate correlations with all other approaches ( $r=0.59-0.79$ ), with the overall lowest correlation observed for Pirotta's method. Despite these lower correlations, the similarity in seasonal trends suggests that SBFI captures similar patterns of foraging activity while also revealing distinct fine scale patterns not fully represented by the other methods. For example, certain peaks identified by the other methods such as the peak from March to April disappeared when applying the SBFI method. Although no independent validation of the vocalization purposes was possible, these small-scale differences are likely the results from the stricter filtering used in SBFI, including the differentiation of search and buzz sequences from social vocalizations based on the acoustic thresholds from the literature (DeRuiter et al. 2009; Migneault et al. 2025; Miller 2008; Pirotta et al. 2014; Sørensen et al. 2018). These social calls are qualified as foraging in the other methods and can thus give slightly different small-scale patterns.

It is important to note that correlation coefficients are more variable when using the BP(10)M rates instead of raw BP(10)M values (Figure A2). As a ratio, the BP(10)M rate amplifies small differences between methods, resulting in a wider spread of correlation values. This highlights how methodological choices in data processing can influence the apparent level of agreement between approaches.

The distance and trend analysis indicated a lot of variability between methods. The foraging methods of DeRuiter and Nuuttila showed near-identical results across all aspects, which is expected due to the fact that both methods only use an upper boundary in ICI ( $<10$  ms) or click rate ( $>125$  clicks/s; ICI  $<8$  ms) that is very close to each other to define a foraging buzz (DeRuiter et al. 2009; Nuuttila et al. 2013). Overall, the SBFI method yielded lower BP10M rates throughout the year across both locations, which is also reflected in the distance analysis. The only exception was Pirotta's method, where estimates fluctuated considerably, with SBFI and Pirotta alternately yielding higher rates depending on the season and site. This variation suggests that environmental or spatial factors may influence method performance.

The observed variation between methods is closely linked to differences in how foraging behavior is defined. Earlier approaches have generally relied on simple acoustic thresholds, such as ICIs or click rates, to identify foraging events (Carlström 2005; DeRuiter et al. 2009; Nuuttila et al. 2013). These methods focused mainly on the distinction between foraging and traveling clicks, as social clicks have been found to partly overlap with the thresholds for foraging, especially when using older versions of PODs that are less detailed in recording and defining click characteristics (Clausen et al. 2011; Migneault et al. 2025; Schaffeld et al. 2016). Similarly, Pirotta's, one of the most frequently applied foraging methods (Benhemma-Le Gall et al. 2021; Berges et al. 2019; N. Todd et al. 2022, 2023, 2025; Williamson et al. 2022), makes use of Gaussian mixture models whose outcomes depend on how

the data is clustered in the three or sometimes four groups (e.g., buzz ICI, regular ICI or long ICI, and sometimes a second regular ICI group) without making a distinction for social communication. Thus, the specific mix of foraging or social behavior at a given location or recording period can alter how these acoustic groups are divided. This overlap means some ICI sequences from social behavior may still be misclassified as foraging. Conversely, true foraging clicks might fall into the regular click category. This is likely happening in the current analysis, as the average buzz click is fairly low at 2.13 ms (Clausen et al. 2011; Migneault et al. 2025; Schaffeld et al. 2016; Sørensen et al. 2018).

More recent methods, such as Schaffeld and our SBFI method, incorporate additional contextual information, such as the presence of a preceding search phase or sudden decrease, to reduce the likelihood of misclassifying non-foraging clicks (Schaffeld et al. 2016). The SBFI method, for example, applies both upper and lower ICI boundaries around known foraging buzz characteristics (average ICI  $\sim 3$  ms), based on results from previous studies using tags and visual observations (DeRuiter et al. 2009; Sørensen et al. 2018), and requires a preceding search/approach click ( $<200$  clicks/s) (Migneault et al. 2025; Miller 2008). This more restrictive definition aims to better distinguish foraging from other high click rate acoustic behaviors. However, a buzz-positive minute may still include both foraging and social activity. In such cases, it is classified as foraging because these behaviors can occur in rapid succession, for example during group hunting (Torres Ortiz et al. 2021). On the other hand, due to porpoise's highly directional echolocation clicks (Berges et al. 2019; Nuuttila et al. 2013; Pirotta et al. 2014), acoustic recording devices will likely not register the entire foraging sequence when the porpoise is not directed towards the hydrophone during the whole foraging event. For this reason, a search/approach click was chosen on top of the refined buzz click interval in the SBFI method, to avoid having to rely on a full foraging sequence while still avoiding selecting repeated social calls as foraging (Migneault et al. 2025; Sørensen et al. 2018). However, we acknowledge that some social behavior could still be present; for example, "wiggles" as indicated by Migneault et al. (2025) could still fall under foraging in our criteria. Similarly, Schaffeld's method which requires a sudden decrease to below 10 ms is likely to include some social behavior if the sudden decrease occurs around the buzz click.

Importantly, most foraging methods acknowledge that some non-foraging signals, such as social or communication clicks, may fall within the same ICI ranges used to define foraging (Clausen et al. 2011; Nuuttila et al. 2013; Pirotta et al. 2014). However, these approaches generally assume that the majority of click sequences within these thresholds are associated with foraging behavior, as those social clicks are assumed to be missed by the POD due to higher directionality (Pirotta et al. 2014) or because they would proportionally occur less as the average group size for harbor porpoises is small (Gilles et al. 2016; Nachtsheim et al. 2021). While this assumption is supported by existing research, it remains difficult to verify what proportion of foraging would then be misclassified especially in periods where higher rates of social communication could be expected due to mating or group hunting (Cervin et al. 2020; Learmonth et al. 2014; Torres Ortiz et al. 2021). Thus, a trade-off still exists between requiring a complete foraging sequence and capturing some potential social behavior.

As such, differences between foraging detection methods should not be interpreted as contradictions, but rather as reflecting varying sensitivities to different components of porpoise acoustic behavior. While absolute estimates of foraging rate differ, the overall consistency in temporal and spatial patterns suggests that these methods capture similar underlying ecological processes. At the same time, the variation observed between methods highlights the importance of carefully considering methodological definitions when comparing results across studies.

## 4.2 | Environmental and Spatial Patterns

The harbor porpoise presence patterns found in Belwind and Faulbaums align with those seen in Calonge et al. (2024) spanning a larger time period, where the least amount of detections is found in summer and the highest amount in winter. This is similar to the patterns found using aerial surveys in Belgian waters where most porpoises were found between February and April and more porpoises were found offshore in winter (Haelters et al. 2011). Belwind (offshore wind farm) and Faulbaums (mid-shore shipping lane) show different seasonal patterns in both presence detections as in foraging rates with a peak in Faulbaums in September that is not found in Belwind. potentially this could be due to small scale differences in prey availability or vessel disturbances.

Harbor porpoises foraging is observed continuously throughout the year with peaks in spring and autumn depending on the location. As a small cetacean with a high metabolism, a high rate of foraging is expected (Booth 2020; MacLeod et al. 2007; Wisniewska et al. 2016). The seasonal patterns for foraging were similar between the different methods. However, a peak in foraging in spring (April) shown by the SBFI method in both locations is less pronounced compared to the other methods. On the other hand, the SBFI method proportionally estimated more foraging during autumn and winter for both locations. Such an increase in foraging rates from summer to autumn aligns with increased energy intake from mid-July to winter with a peak in mid-November (R. A. Kastelein et al. 2018; Rojano-Doñate et al. 2018). The lower peak of foraging during spring identified by the SBFI method could be due to a higher proportion of social calls related to mating activity occurring in spring (April–June) (Keener et al. 2018; Smith et al. 2026; Webber et al. 2023) that might be misclassified as foraging in other methods. However, as social and sexual interactions have been documented throughout the year (Elliser et al. 2025), this explanation cannot be confirmed with certainty, and additional acoustic data are needed to reliably confirm these behaviors. Additionally, food intake for North Sea porpoises typically reached a minimum during April (Rojano-Doñate et al. 2018), which could explain the lower amount of foraging. High foraging rates might also indicate targeted feeding on smaller, low-energy prey. These differences in foraging activity could hypothetically relate to variations in prey size or quality (Leopold et al. 2015; Sveegaard et al. 2012).

However, this does not explain the difference in foraging seasonal patterns between both locations. While Pirotta's BP10M rates follow the other methods patterns in foraging in Belwind, in Faulbaums the pattern is less similar with a proportionally bigger "dip" in summer that is not as pronounced in other methods.

These differences in correlation between methods across locations likely reflect both site-specific porpoise behavior and environmental conditions such as different prey around different habitats or more background noise at some locations. Methods may differ in how strictly they capture foraging versus for example social vocalizations, and this discrepancy becomes more apparent in locations where porpoises vocalize more frequently or where background noise is higher, affecting foraging detection rates and method agreement. While seasonal differences in foraging rates can be seen in our yearly data on a small scale, different foraging rates have been found before comparing countries with different latitudes, supporting the importance of environmental conditions on their behavior (Stavenow Jerremalm et al. 2025).

## 4.3 | Advantages and Recommendations

In the absence of methods to ground-truth porpoise foraging behavior in the wild, this analysis provides a systematic overview and comparison of the results across different foraging methods. Observed patterns were robust across methods, indicating that results from different papers could be broadly compared with each other, even if absolute magnitudes differ. Thus, when trying to identify broad-scale spatial distributions, seasonal occupancy, or relative temporal patterns, all evaluated methods could be used as they yield highly consistent results. As the SBFI method is based on information gathered from several studies that used visual observations, tags, and hydrophones to record and distinguish between foraging and social or traveling behavior, the thresholds applied are supported by prior research. In this context, method choice becomes more important when studies aim to quantify absolute foraging effort or assess habitats or periods characterized by high porpoise densities or frequent social interactions such as mating periods. The SBFI method would then be recommended to avoid overestimating foraging activity.

Knowledge of harbor porpoise behavior, and particularly foraging behavior, can support policy and management by enabling the identification of critical feeding habitats and the temporal patterns in which these areas are used. Such information is essential for the effective spatial and temporal planning of human activities, reducing disturbance or making use of the artificial reefs (Booth 2020; V. Todd et al. 2009; Wisniewska et al. 2016).

Future research should aim to further validate these approaches by combining acoustic click data from PODs with visual behavioral observations and/or high-resolution biologging tags (e.g., D-tag) (DeRuiter et al. 2009; Wisniewska et al. 2016) as those tags or cameras can provide additional information that POD data does not have such as prey echoes and jerks also known as sudden accelerations that signal a head-jolt or strike maneuver as well as visual confirmation. This integration would provide direct ground-truthing, especially during a period where many studies are trying to disentangle both. Additionally, applying multiple foraging detection methods to the same datasets, as done in this study, but across broader geographical locations, remains valuable to assess the robustness of conclusions across regions and if not to find the driving factors behind these differences.

## 5 | Conclusion

Foraging analysis methods exhibit strong agreement in relative patterns and temporal trends, even if some diverged in magnitude or showed context-dependent biases, particularly under specific seasonal or spatial conditions. The newly proposed SBFi foraging analysis method exhibited good correlation and similarity with the other frequently used methods while offering a more targeted and straightforward analytical framework. Importantly, it provides a crucial step forward in distinguishing foraging buzzes from social communication calls. Future studies integrating acoustic tags or tags equipped with a camera would further support validation of foraging behavior and help to disentangle foraging from other acoustic behaviors. Knowledge of harbor porpoise foraging behavior is crucial for informing effective conservation and management, as it enables the identification of key feeding areas, supports the mitigation of human impacts, and contributes to ecosystem-based management. Improving the accuracy of behavioral classification will further strengthen the application of such data in policy and decision-making.

### Author Contributions

**Sofya Aoufi:** conceptualization, investigation, methodology, formal analysis, writing – review and editing, writing – original draft, data curation, visualization, validation. **Bob Rumes:** supervision, writing – review and editing, funding acquisition, data curation, conceptualization. **Jan Vanaverbeke:** writing – review and editing, methodology. **Steven Degraer:** funding acquisition, writing – review and editing, supervision. **Elisabeth Debusschere:** conceptualization, data curation, writing – review and editing, supervision, investigation.

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ChatGPT-5 mini (accessed March 2026) was used to reorganize the Discussion section for clarity and flow. All AI-assisted text was reviewed and revised by the authors to ensure accuracy and clarity of meaning.

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### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data that support the findings of this study are openly available in LifeWatch observatory data: Inter-click intervals of harbour at <https://doi.org/10.14284/786>.

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## Appendix A

### Search Strategy and Selection Criteria for the Literature Study

To establish the foundation for selecting the benchmark methodologies, we conducted a systematic literature review. Databases searched included Scopus, Web of Science, and Google Scholar for peer-reviewed studies published between 1995 and 2025.

The following search string was applied: (“harbor porpoise” OR “*Phocoena phocoena*”) AND (“foraging” OR “behavior” OR “clicks” OR “communication”).

Inclusion and Exclusion Criteria: Papers were retained if they assessed wild harbor porpoise foraging behavior using static/passive acoustic monitoring (PAM) devices or acoustic data-logging tags. Studies were omitted if they relied on identical methodologies to previously selected papers or did not present unique, reproducible acoustic criteria.

Through title, abstract, and methodological screening, the initial search results were refined to 42 key research papers (detailed in Table A1). From these, four distinct, highly reproducible methodologies were selected for the main comparative analysis based on their uniqueness and widespread use in the literature.

**TABLE A1** | Summary of papers retained in the review after first checks.

| No. | Authors                                                                       | Title                                                                                                                          | Method                                                  | Tools                                | Retained | Reason                                                | Year |
|-----|-------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------|--------------------------------------|----------|-------------------------------------------------------|------|
| 1   | Verboom, Kastelein                                                            | Acoustic signals by harbour porpoises ( <i>Phocoena phocoena</i> )                                                             | —                                                       | Hydrophone amplifiers, tape recorder | No       | Descriptive acoustics no foraging                     | 1995 |
| 2   | Verboom, Kastelein                                                            | Structure of harbour porpoise ( <i>Phocoena phocoena</i> ) acoustic signals with high repetition rates                         | —                                                       | Hydrophone and tape recorder         | No       | Descriptive acoustics only, no foraging               | 2003 |
| 3   | Carlström                                                                     | Diel variation in echolocation behavior of wild harbor porpoises                                                               | Trains with minimum ICI < 10 ms = foraging event        | T-POD                                | Yes      | ICI < 10 ms as method                                 | 2005 |
| 4   | Akamatsu, Teilmann, Miller, Tougaard, Dietz, D. Wang, K. Wang, Siebert, Naito | Comparison of echolocation behaviour between coastal and riverine porpoises                                                    | —                                                       | A-tag with suction cup               | No       | No foraging behavior mentioned                        | 2007 |
| 5   | Koschinski, Diederichs, Amundin                                               | Click train patterns of free-ranging harbour porpoises acquired using T-PODs may be useful as indicators of their behaviour    | Feeding behavior click train if decrease in ICI < 10 ms | T-POD                                | No       | Similar to Carlström (2005)                           | 2008 |
| 6   | DeRuiter, Bahr, Blanchet, Hansen, Kristensen, Madsen, Tyack, Wahlberg         | Acoustic behaviour of echolocating porpoises during prey capture                                                               | Buzz = time period where clickrate > 125 clicks/s       | Modified D-tag                       | Yes      | Description foraging behavior click rates             | 2009 |
| 7   | Verfuss, Miller, Pilz, Schnitzler                                             | Echolocation by two foraging harbour porpoises ( <i>Phocoena phocoena</i> )                                                    | —                                                       | Hydrophones, camera's                | No       | Descriptive foraging behavior without foraging method | 2009 |
| 8   | V. Todd, Pearse, Tregenza, Lepper, I. Todd                                    | Diel echolocation activity of harbour porpoises ( <i>Phocoena phocoena</i> ) around North Sea offshore gas installations       | Carlström (2005)                                        | T-POD                                | No       | No unique foraging method                             | 2009 |
| 9   | Clausen, Wahlberg, Beedholm, DeRuiter, Madsen                                 | Click communication in harbour porpoises <i>Phocoena phocoena</i>                                                              | —                                                       | Hydrophone                           | No       | Descriptive acoustics                                 | 2010 |
| 10  | Miller                                                                        | Prey capture by harbor porpoises ( <i>Phocoena phocoena</i> ): A comparison between echolocators in the field and in captivity | —                                                       | —                                    | No       | Descriptive acoustics foraging behavior, click rates  | 2010 |
| 11  | Linnenschmidt                                                                 | Biosonar, dive, and foraging activity of satellite tracked harbor porpoises ( <i>Phocoena phocoena</i> )                       | —                                                       | A-tag                                | No       | Descriptive acoustics                                 | 2012 |
| 12  | Wisniewska, Johnson, Beedholm, Wahlberg, Madsen                               | Acoustic gaze adjustments during active target selection in echolocating porpoises                                             | ICI < 13 ms = foraging buzz                             | D-TAG, hydrophone, underwater camera | No       | Method similar to Carlström                           | 2012 |

(Continues)

TABLE A1 | (Continued)

| No. | Authors                                                                                                                       | Title                                                                                                                                                                        | Method                                                  | Tools        | Retained | Reason                                                                                                                | Year |
|-----|-------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------|--------------|----------|-----------------------------------------------------------------------------------------------------------------------|------|
| 13  | Wegner Denise, Koschinski Sven                                                                                                | Harbour porpoise ( <i>Phocoena phocoena</i> Linnaeus, 1758) entering the Weser river after decades of absence                                                                | —                                                       | CPOD         | No       | Method refers to previous paper of Koschinski et al. (2008)                                                           | 2012 |
| 14  | Nuutila, Meier, Evans, Turner, Bennell, Hiddink                                                                               | Identifying foraging behaviour of wild bottlenose dolphins ( <i>Tursiops truncatus</i> ) and harbour porpoises ( <i>Phocoena phocoena</i> ) with static acoustic dataloggers | ICI < 10 ms = foraging buzz                             | C-POD        | Yes      | Method similar to Carlström but methodology better described thus this will be used as reference instead of Carlström | 2013 |
| 15  | Pirotta, Thompson, Miller, Brookes, Cheney, Barton, Graham, Lusseau                                                           | Scale-dependent foraging ecology of a marine top predator modelled using passive acoustic data                                                                               | Gaussian mixture models with three groups of ICI's      | T-POD, C-POD | Yes      | Unique method                                                                                                         | 2014 |
| 16  | Pirotta, Brookes, Graham, Thompson                                                                                            | Variation in harbour porpoise activity in response to seismic survey noise                                                                                                   | Pirotta et al. (2014)                                   | C-POD        | No       | Method from pirotta                                                                                                   | 2014 |
| 17  | Schaffeld, Brüger, Gallus, Dähne, Krügel, Herrmann, Jabbusch, Ruf, Verfuss, Benke, Koblitiz                                   | Diel and seasonal patterns in acoustic presence and foraging behaviour of free-ranging harbour porpoises                                                                     | Several criteria to be fulfilled within a 10-min period | T-POD        | Yes      | Unique method                                                                                                         | 2016 |
| 18  | Wisniewska Danuta Maria, Johnson Mark, Teilmann Jonas, A. Miller Lee, Siebert Ursula, Madsen Peter Teglbjerg                  | Ultra-high foraging rates of harbor porpoises make them vulnerable to anthropogenic disturbance                                                                              | ICI < 8 ms                                              | Dtag         | No       | Similar to DeRuiter et al. (2009)                                                                                     | 2016 |
| 19  | Benjamins, van Geel, Hastie, Elliott, Wilson                                                                                  | Harbour porpoise distribution can vary at small spatiotemporal scales in energetic habitats                                                                                  | —                                                       | C-POD        | No       | Only presence/occurrence                                                                                              | 2017 |
| 20  | Williamson, Brookes, Scott, Graham, Thompson                                                                                  | Diurnal variation in harbour porpoise detection – potential implications for management                                                                                      | Pirotta et al. (2014)                                   | C-POD        | No       | No unique foraging method                                                                                             | 2017 |
| 21  | Nuutila, Bertelli, Mendzil, Dearle                                                                                            | Seasonal and diel patterns in cetacean use and foraging at a potential marine renewable energy site                                                                          | Nuutila et al. (2013)                                   | C-POD        | No       | No unique foraging method                                                                                             | 2017 |
| 22  | Wingfield Jessica E., O'Brien Michael, Lyubchich Vyacheslav, J. Roberts Jason, N. Halpin Patrick, N. Rice Aaron, Bailey Helen | Year-round spatiotemporal distribution of harbour porpoises within and around the Maryland wind energy area                                                                  | Carlstrom et al. (2006)                                 | CPOD         | No       | No unique foraging method                                                                                             | 2017 |
| 23  | Sørensen, Wisniewska, Jensen, Johnson, Teilmann, Madsen                                                                       | Click communication in wild harbour porpoises ( <i>Phocoena phocoena</i> )                                                                                                   | —                                                       | DTAG         | No       | Descriptive acoustic behavior                                                                                         | 2018 |
| 24  | Wisniewska, Johnson, Teilmann, Siebert, Galatius, Dietz, Madsen                                                               | High rates of vessel noise disrupt foraging in wild harbour porpoises ( <i>Phocoena phocoena</i> )                                                                           | ICI < 15 ms = foraging buzz                             | D-TAGs       | No       | Method similar to Carlström                                                                                           | 2018 |

(Continues)

TABLE A1 | (Continued)

| No. | Authors                                                                                                                    | Title                                                                                                                                                                       | Method                                                        | Tools        | Retained                  | Reason                      | Year |
|-----|----------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------|--------------|---------------------------|-----------------------------|------|
| 25  | Berges, Geelhoed, Scheidat, Tougaard                                                                                       | Quantifying harbour porpoise foraging behaviour in C-POD data: identification, automatic detection and potential application                                                | Pirotta et al. (2014), Schaffeld et al. (2016), Miller (2008) | C-POD        | No                        | No unique foraging method   | 2019 |
| 26  | Zein, Woelfing, Dähne, Schaffeld, Ludwig, Rye, Baltzer, Ruser, Siebert                                                     | Time and tide: seasonal, diel and tidal rhythms in Wadden Sea harbour porpoises ( <i>Phocoena phocoena</i> )                                                                | Carlström (2005)                                              | C-POD, T-POD | No                        | No unique foraging method   | 2019 |
| 27  | Gustafsson                                                                                                                 | Pearls as bycatch mitigation strategy for harbour porpoise ( <i>Phocoena phocoena</i> )                                                                                     | Wisniewska et al. (2012)                                      | F-POD        | No unique foraging method | No unique foraging method   | 2020 |
| 28  | Todd, Cronin, Luck, Bennison, Jessopp, Kavanagh                                                                            | Using passive acoustic monitoring to investigate the occurrence of cetaceans in a protected marine area in northwest Ireland                                                |                                                               | C-POD        | No                        | Only presence/occurrence    | 2020 |
| 29  | Maeda Saki, Sakurai Kenji, Akamatsu Tomonari, Matsuda Ayaka, Yamamura Orio, Kobayashi Mari, Matsuishi Takashi Fritz        | Foraging activity of harbour porpoises around a bottom-gillnet in a coastal fishing ground, under the risk of bycatch                                                       | Variation on Schaffeld et al. (2016)                          | A-tag        | No                        | No unique foraging method   | 2021 |
| 30  | Benhemma-Le Gall, Graham, Merchant, Thompson                                                                               | Broad-scale responses of harbour porpoises to pile-driving and vessel activities during offshore windfarm construction                                                      | Pirotta et al. (2014)                                         | C-POD        | No                        | No unique foraging method   | 2021 |
| 31  | Clausen Tubbert Karin, Teilmann Jonas, Wisniewska Danuta M., Balle Jeppe Dalgaard, Delefosse Matthieu, M. van Beest Floris | Echolocation activity of harbour porpoises, <i>Phocoena phocoena</i> shows seasonal artificial reef attraction despite elevated noise levels close to oil and gas platforms | ICI < 15 ms                                                   | CPOD         | No                        | Method similar to Carlström | 2021 |
| 32  | Williamson, Scott, Laxton, Bachl, Illian, Brookes, Thompson                                                                | Spatiotemporal variation in harbor porpoise distribution and foraging across a landscape of fear                                                                            | Pirotta et al. (2014)                                         | C-POD        | No                        | No unique foraging method   | 2022 |
| 33  | Fernandez-Betelu, Graham, Thompson                                                                                         | Reef effect of offshore structures on the occurrence and foraging activity of harbour porpoises                                                                             | Pirotta et al. (2014)                                         | C-POD        | No                        | No unique foraging method   | 2022 |
| 34  | Todd, Jessopp, Rogan, Kavanagh                                                                                             | Extracting foraging behavior from passive acoustic monitoring data to better understand harbor porpoise ( <i>Phocoena phocoena</i> ) foraging habitat use                   | Pirotta et al. (2014)                                         | C-POD        | No                        | No unique foraging method   | 2022 |
| 35  | Todd, Kavanagh, Rogan, Jessopp                                                                                             | What the F-POD? Comparing the F-POD and C-POD for monitoring of harbor porpoise ( <i>Phocoena phocoena</i> )                                                                | Pirotta et al. (2014)                                         | C-POD, F-POD | No                        | No unique foraging method   | 2023 |
| 36  | Stedt, Wahlberg, Carlström, Nilsson, Amundin, Oskolkov, Carlsson                                                           | Micro-scale spatial preference and temporal cyclicity linked to foraging in harbour porpoises                                                                               | Carlström (2005)                                              | C-POD        | No                        | No unique foraging method   | 2023 |

(Continues)

TABLE A1 | (Continued)

| No. | Authors                                                                                                   | Title                                                                                                                                                                                 | Method                 | Tools | Retained | Reason                                                      | Year |
|-----|-----------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|-------|----------|-------------------------------------------------------------|------|
| 37  | Holdman, Tregenza, Van Parijs, DeAngelis                                                                  | Acoustic ecology of harbour porpoise ( <i>Phocoena phocoena</i> ) between two U.S. offshore wind energy areas                                                                         | Carlström (2005)       | F-POD | No       | No unique foraging method                                   | 2023 |
| 38  | Fernandez-Betelu, Graham, Malcher, Webster, Cheong, Wang, Iorio-Merlo, Robinson, Thompson                 | Characterising underwater noise and changes in harbour porpoise behaviour during the decommissioning of an oil and gas platform                                                       | Stedt et al. (2023)    | C-POD | No       | No unique foraging method                                   | 2024 |
| 39  | Owen, Carlström, Eriksson, Andersson, Nordström, Lalander, Sveegaard, Kyh, Griffiths, Cosentino, Tougaard | Rerouting of a major shipping lane through important harbour porpoise habitat caused no detectable change in annual occurrence or foraging patterns                                   | Nuuttila et al. (2013) | C-POD | No       | No unique foraging method                                   | 2024 |
| 40  | Migneault Amy, Dracott Karina, Tregenza Nick, Robinson Chloe V.                                           | Reading between the lines: Novel insights on wild Pacific harbour porpoise ( <i>Phocoena phocoena vomerina</i> ) social communication through narrow-band high frequency click trains | —                      | F-POD | No       | Do not calculate foraging but focus on social communication | 2025 |
| 41  | Dracott Karina, V. Robinson Chloe, Dares Lauren, Woodley Erin, Migneault Amy, Birdsall Caitlin            | Influence of vessel disturbance on Pacific harbour porpoise ( <i>Phocoena phocoena vomerina</i> ) echolocation                                                                        | Carlström (2005)       | CPOD  | No       | No unique foraging method                                   | 2025 |
| 42  | R. E. Todd Nicole, J. Jessop Mark, Rogan Emer, S. Kavanagh Ailbhe                                         | Multi-year acoustic monitoring reveals fine-scale habitat preferences of harbour porpoise ( <i>Phocoena phocoena</i> ) and species decline within a Special Area of Conservation      | Pirotta et al. (2014)  | CPOD  | No       | No unique foraging method                                   | 2025 |

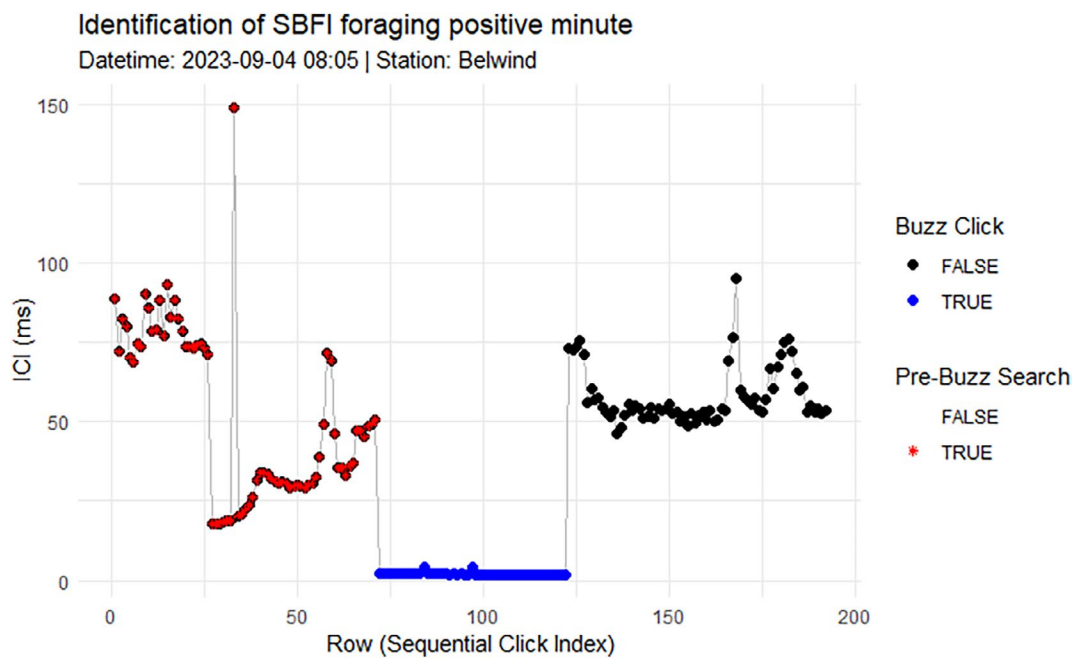


FIGURE A1 | Example of a foraging positive minute defined according to the SBFI method.

### Correlation between BP(10)M methods

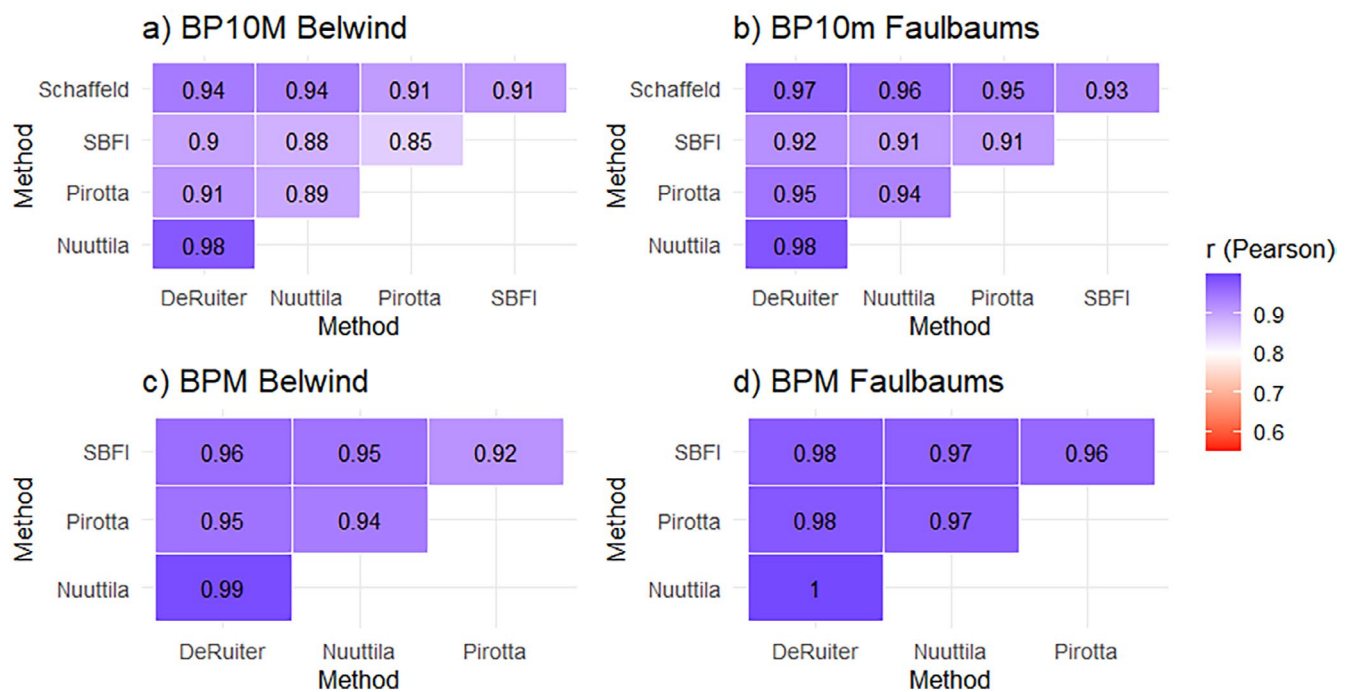


FIGURE A2 | Correlation coefficients between methods for BP10M and BPM values at Belwind (a, c) and Faulbaums (b, d).

**TABLE A2** | Distance and trend analysis for methods using BP10M rate in Belwind.

| Comparison of BP10M rate methods through distance and trend analysis in Belwind |               |                |             |             |                |
|---------------------------------------------------------------------------------|---------------|----------------|-------------|-------------|----------------|
| Mean and variability of pairwise differences with trend, slope, and <i>p</i>    |               |                |             |             |                |
| Method pair                                                                     | Mean distance | SD of distance | Relative SD | Trend slope | Slope <i>p</i> |
| diff_3_4                                                                        | 0.015         | 0.328          | 22.560      | −2E−05      | 0.000          |
| diff_1_2                                                                        | −0.031        | 0.142          | 4.600       | 0E+00       | 0.072          |
| diff_3_5                                                                        | −0.048        | 0.272          | 5.710       | −1E−05      | 0.014          |
| diff_4_5                                                                        | −0.062        | 0.260          | 4.190       | 1E−05       | 0.003          |
| diff_1_5                                                                        | 0.070         | 0.231          | 3.310       | 0E+00       | 0.938          |
| diff_2_5                                                                        | 0.101         | 0.250          | 2.480       | 0E+00       | 0.274          |
| diff_1_3                                                                        | 0.117         | 0.265          | 2.260       | 1E−05       | 0.010          |
| diff_1_4                                                                        | 0.132         | 0.276          | 2.090       | −1E−05      | 0.006          |
| diff_2_3                                                                        | 0.148         | 0.294          | 1.980       | 1E−05       | 0.001          |
| diff_2_4                                                                        | 0.163         | 0.301          | 1.850       | −1E−05      | 0.091          |

**TABLE A3** | Distance and trend analysis for methods using BP10M rate in Faulbaums.

| Comparison of BP10M rate methods through distance and trend analysis in Faulbaums |               |                |             |             |                |
|-----------------------------------------------------------------------------------|---------------|----------------|-------------|-------------|----------------|
| Mean and variability of pairwise differences with trend, slope, and <i>p</i>      |               |                |             |             |                |
| Method pair                                                                       | Mean distance | SD of distance | Relative SD | Trend slope | Slope <i>p</i> |
| diff_3_5                                                                          | −0.031        | 0.244          | 7.820       | 0E+00       | 0.314          |
| diff_1_2                                                                          | −0.035        | 0.158          | 4.500       | −1E−05      | 0.019          |
| diff_3_4                                                                          | 0.056         | 0.312          | 5.590       | −1E−05      | 0.008          |
| diff_1_5                                                                          | 0.057         | 0.222          | 3.880       | 1E−05       | 0.082          |
| diff_4_5                                                                          | −0.087        | 0.263          | 3.020       | 1E−05       | 0.027          |
| diff_1_3                                                                          | 0.089         | 0.235          | 2.650       | 1E−05       | 0.007          |
| diff_2_5                                                                          | 0.092         | 0.248          | 2.680       | 1E−05       | 0.002          |
| diff_2_3                                                                          | 0.124         | 0.276          | 2.230       | 2E−05       | 0.000          |
| diff_1_4                                                                          | 0.144         | 0.288          | 2.000       | 0E+00       | 0.505          |
| diff_2_4                                                                          | 0.180         | 0.317          | 1.760       | 0E+00       | 0.563          |

**TABLE A4** | Distance and trend analysis for methods using BPM rate in Belwind.

| Comparison of BPM rate methods through distance and trend analysis in Belwind |               |                |             |             |                |
|-------------------------------------------------------------------------------|---------------|----------------|-------------|-------------|----------------|
| Mean and variability of pairwise differences with trend, slope, and <i>p</i>  |               |                |             |             |                |
| Method pair                                                                   | Mean distance | SD of distance | Relative SD | Trend slope | Slope <i>p</i> |
| diff_3_4                                                                      | 0.021         | 0.267          | 12.730      | −2E−05      | 0.000          |
| diff_1_2                                                                      | −0.033        | 0.126          | 3.810       | 0E+00       | 0.302          |
| diff_1_3                                                                      | 0.110         | 0.220          | 2.000       | 1E−05       | 0.003          |
| diff_1_4                                                                      | 0.131         | 0.235          | 1.800       | −1E−05      | 0.010          |
| diff_2_3                                                                      | 0.143         | 0.250          | 1.750       | 1E−05       | 0.002          |
| diff_2_4                                                                      | 0.164         | 0.259          | 1.580       | −1E−05      | 0.065          |

**TABLE A5** | Distance and trend analysis for methods using BPM rate in Faulbaums.

| Comparison of BPM rate methods through distance and trend analysis in Faulbaums |               |                |             |             |                |
|---------------------------------------------------------------------------------|---------------|----------------|-------------|-------------|----------------|
| Mean and variability of pairwise differences with trend, slope, and <i>p</i>    |               |                |             |             |                |
| Method pair                                                                     | Mean distance | SD of distance | Relative SD | Trend slope | Slope <i>p</i> |
| diff_1_2                                                                        | −0.035        | 0.129          | 3.640       | −1E−05      | 0.003          |
| diff_3_4                                                                        | 0.053         | 0.251          | 4.760       | −1E−05      | 0.023          |
| diff_1_3                                                                        | 0.083         | 0.187          | 2.260       | 1E−05       | 0.002          |
| diff_2_3                                                                        | 0.118         | 0.224          | 1.900       | 2E−05       | 0.000          |
| diff_1_4                                                                        | 0.136         | 0.234          | 1.730       | 0E+00       | 0.957          |
| diff_2_4                                                                        | 0.171         | 0.259          | 1.510       | 1E−05       | 0.117          |