

An Invasive Species Surveillance and Monitoring Framework for the Island of Ireland

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Chapter 2. Sampling Design



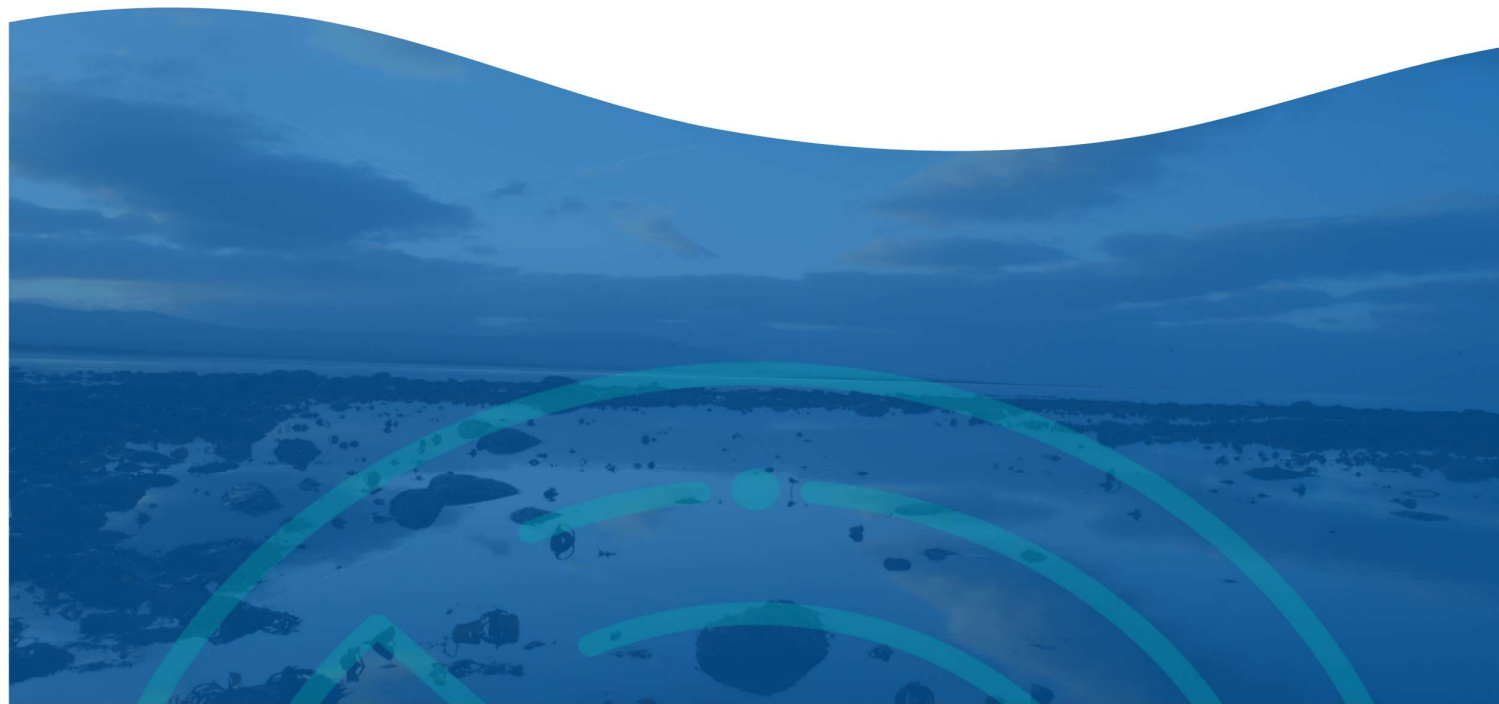
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1 Monitoring Programme Sampling Design Simulation

1.1 Overview

A simulation-based approach was developed and applied, based on a model published by Gibson et al., (2025), to explore how different invasive species monitoring designs perform. A total number of sites is specified, and each site is assigned a risk score based on a specified theoretical risk distribution (i.e., uniform, normal, or exponential risk). At the beginning of each simulation, a defined number of sites with a high-risk score are 'seeded' with an invasive species, representing the introduction of an invasive species into the site. For the simulation, it is assumed that invasive species are introduced at the beginning of the simulation only (time 0) and remain present for the duration of the simulation. It is also assumed that the ability to detect the invasive species is constant over time and across all sites.

The number of sites to be sampled is defined and the specific sites to be sampled (i.e., surveyed for invasive species) are selected according to a specified sampling approach (e.g., random, risk-based). For the purpose of site selection, it is assumed that site risk is known without error. Sampling frequency is defined and represents the assumed frequency with which sites are surveyed for invasive species (e.g., once a year, once every six years)

A method sensitivity is set which determines the likelihood of an invasive species being detected at a site where it is present during a survey (i.e., a sensitivity of 0.5 indicates that there is a 50% likelihood of the invasive species being detected if the site where it is present is surveyed).

The key outputs of the simulation are time to invasive species detection and probability of invasive species detection.

1.1.1 Parameters

The total number of sites was set to 400. A number of scenarios, representing unique combinations of five key monitoring programme design parameters, and their associated categories, were run. The parameters and their categories are described below.

Site risk: Three different site risk distributions were used to provide insight into the interplay between site risk distribution and other monitoring programme designs elements. Sites were assigned a risk according to three different risk distributions:

- Uniform – all sites have an equal risk of invasive species introduction and establishment.
- Normal – invasive species introduction and establishment risk follows a normal distribution with most sites having intermediate risk and a small number of sites having low or high risk.
- Exponential - invasive species introduction and establishment risk follows an exponential distribution with most sites having low risk and a small number of sites having high risk.

Sampling approach: Site selection varied in risk focus, to facilitate evaluation of whether targeting high risk sites improves invasive species detection. Three sampling approaches were applied:

- Random – sites to be monitored were selected at random, regardless of their risk of introduction and establishment.
- Risk-weighted – sites to be monitored were selected based on their risk level. High risk sites were preferentially selected for monitoring over low risk sites; however low risk sites could still be selected.
- High-risk only – only the highest risk sites are selected for monitoring, with these sites being monitored repeatedly.

Method sensitivity: The sensitivity of survey method to detect invasive species presence was defined to explore how method sensitivity may impact invasive species detection. Two sensitivities were included, representing low and high sensitivity:

- 0.5 – indicating a relatively insensitive method where, if present, a species is detected only 50% of the time.
- 0.9 – a more sensitive method where, if present, a species is detected 90% of the time.

Number of sampled sites: The average number of sites monitored per year was varied to capture different monitoring effort (and therefore monitoring programme cost), and their impact on invasive species detection:

- 20 sites – reflecting a more modest monitoring programme.
- 40 sites – reflecting a larger monitoring programme.

Sampling frequency: Two sampling frequencies were simulated to explore how the interval between sampling of sites may affect the likelihood and speed of invasive species detection:

- Sampling every year – sampling is conducted every year, with some sites monitored repeatedly between years (depending on the sampling approach).
- Sampling every six years – sampling is conducted only every sixth year. For example, with an average number of sites per year of 20, this frequency would result in 120 sites being sampled in year 5, 11, 17, etc. and no sites sampled (and monitored) in the intervening years. Some sites may be monitored repeatedly during every sampling year and some sites may not (depending on the sampling approach).

1.1.2 Outputs

Simulations were run across 25 years. For each scenario, 1000 simulations were run and the median time to detection as well as the probability of detection at set points in time (one year, five years, and ten years) was determined. The number of simulations in which the invasive species failed to be

detected was also recorded. As multiple sites were initially seeded with an invasive species, results of the simulations were calculated for the first detection (i.e., detecting invasive species in any one of the 10 seeded sites), the fifth detection (i.e., detecting invasive species in five of the 10 seeded sites), and the tenth detection (i.e., detecting invasive species in all ten seeded sites).

A number of key observations were made from the outputs of the simulations:

- Median time to first detection (10% seeded sites) ranged from 0.25 (number of sites: 40; sampling frequency: annual; sampling approach: high-risk only; site risk distribution: exponential; method sensitivity: 0.9) to 5.49 years (number of sites: 20; sampling frequency: six years; sampling approach: random; site risk distribution: positive normal; method sensitivity: 0.5) (Figure 1a).
- Median time to fifth detection (50% seeded sites) ranged from one (number of sites: 40; sampling frequency: annual; sampling approach: high-risk only; site risk distribution: exponential; method sensitivity: 0.9) to 18 years (number of sites: 20; sampling frequency: annual; sampling approach: random; site risk distribution: exponential; method sensitivity: 0.5 and number of sites: 20; sampling frequency: annual; sampling approach: risk-weighted; site risk distribution: random uniform; method sensitivity: 0.5) (Figure 1b).
- Median time to 10th detection (100% seeded sites) ranged from 6.1 (number of sites: 20 sampling frequency: six years; sampling approach: high-risk only; site risk distribution: positive normal; method sensitivity: 0.9) to 24.1 (number of sites: 20; sampling frequency: annual; sampling approach: random; site risk distribution: random uniform; method sensitivity: 0.5) years (Figure 1c)
- Time to first detection is lower under annual sampling than six-year sampling. This relatively lower time to first detection is particularly apparent when coupled with a greater number of sampled sites (Figure 1).
- Time to detection and detection failure was consistently lower under scenarios incorporating higher method sensitivity (Figure 1).
- Variation in time to detection and detection failure was very low across risk weighted and random sampling approaches (Figure 2)
- Time to fifth detection (i.e., detection of five (50%) seeded sites) was similar for annual and 6-year sampling frequencies. An increase in the number of sites improves the time to detection for risk weighted and random sampling approaches relative to high risk only sampling approach under a 6-year sampling frequency (Figure 1b).
- While time to fifth detection was lowest for programmes which monitored only high-risk sites, detection failure was highest for these programmes relative to other sampling approaches, in particular when coupled with high method sensitivity, a greater number of sites and an annual sampling frequency. However, detection failure was relatively lower when site risk distribution was exponential (i.e., when most sites have low risk but a small

proportion of sites have high risk of invasive species introduction and establishment), in particular when coupled with a small number of sites and a six-year sampling frequency (Figure 1b, Figure 2a).

- Failure to detect invasive species was lower when the monitoring programme covered more sites (Figure 2).
- Failure to detect invasive species was lowest under a six-year sampling frequency. (Note that this may be due to the fact that while the same total number of sites remains the same, under annual sampling, the same site might be sampled multiple times across a six year period, whereas under a six-year sampling, sites sampled are unique across the six year period) (Figure 2).
- Under some scenarios, monitoring failed to detect invasive species at all 10 seeded sites over the course of the monitoring programme (25 years).

1.1.3 Implications for monitoring programme design

- The greater the number of sites monitored, the greater the probability of detection and the lower the time to detection.
- If method sensitivity is low and cannot be improved, this can be offset by increasing the number of sites to improve the probability of detection.
- If the number of sites cannot be increased, this can be offset by increasing method sensitivity to improve the probability of detection.
- Annual sampling reduces the time to first detection, if a detection is made. However, annual sampling is also associated with greatest detection failure (though the difference in time to detection between sampling frequencies reduces for fifth detection). This is likely driven by the fact that under annual sampling, the same site can be monitored each year such that the number of unique sites monitored over six-year period under annual sampling is less than the number of unique sites monitored over six-year period under six-year sampling. Therefore, annual sampling at novel unsampled sites can be inferred as the most effective approach for detection
- An understanding of site risk distribution is important when selecting sampling approach – a focus on high-risk sites only is effective under limited circumstances (assuming that site risk calculation is accurate).
- There is a trade-off between time to detection and probability of detection. This is particularly apparent for a high-risk site only sampling approach, where if an invasive species is detected at a seeded site, it is detected in a short period of time, but the probability of detecting an invasive species is low. This is because an introduction (seeding) of invasive species into a lower-risk site is still possible but will not be detected as these sites are not monitored under a high-risk site-only sampling approach. Inclusion of low-risk sites, even at low frequency, will improve the detection probability.

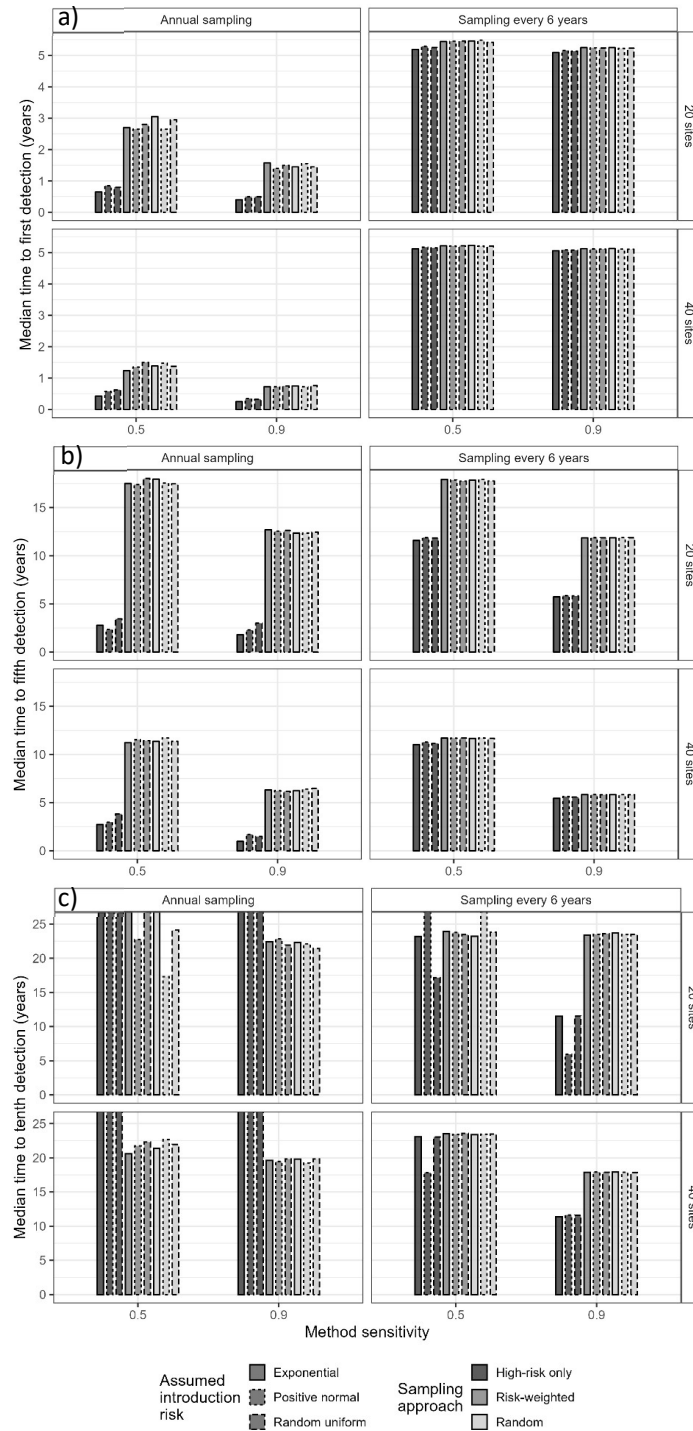


Figure 1. Time to detection of invasive species at one (10%) (a, top) five (50%) (b, middle), and ten (100%) (c, bottom) of the seeded sites according to the sampling frequency (columns), number of sites (rows), method sensitivity (x axis), sampling approach (shading) and introduction risk (line type). Note that a median time to detection of greater than 25 years indicates detection failure within the simulated timeframe (see Figure 2).

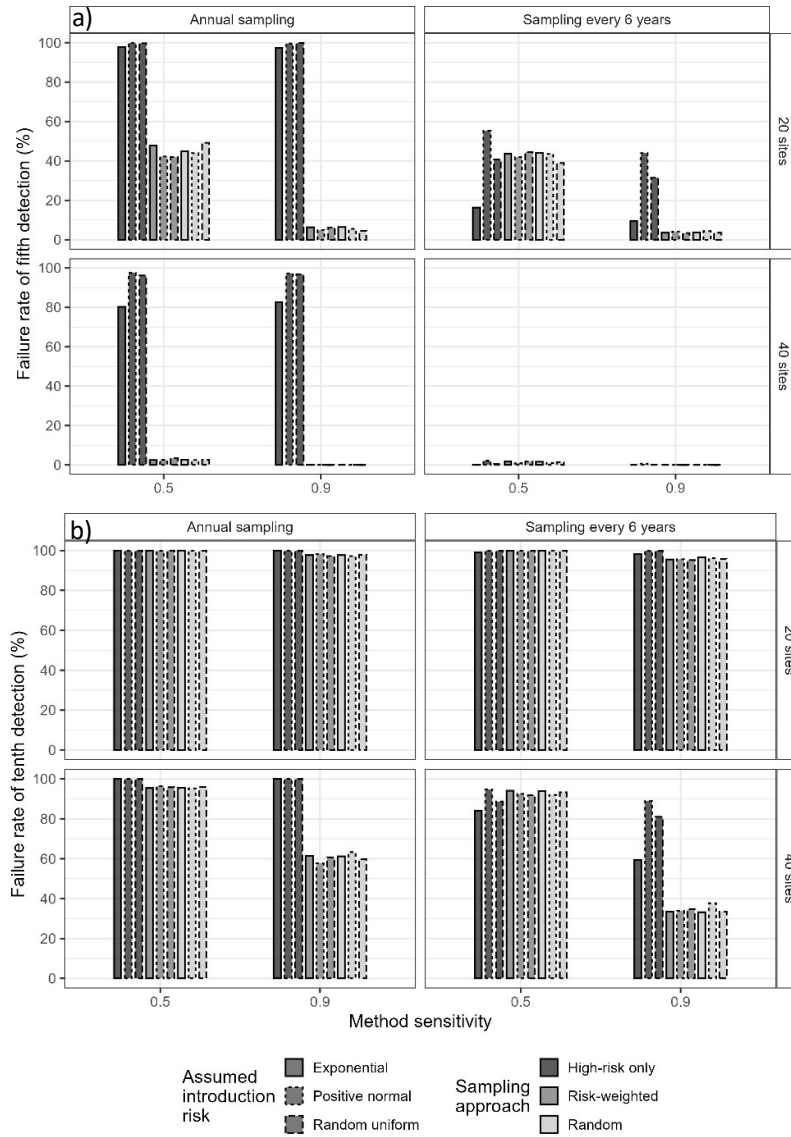


Figure 2. Failure to detect invasive species at a) five (50%) and b) ten (100%) of the seeded sites according to the sampling frequency (columns), number of sites (rows), methods sensitivity (x axis), sampling approach (shading) and introduction risk (line type).

2 Power analysis

2.1 Overview

Power analyses are used to determine the likelihood of detecting a statistically significant change or trend, assuming a trend of a certain magnitude actually exists. Here, we used a power analysis to examine how the probability of detection in the first year after introduction, estimated by the simulations, affects the power to detect a positive trend in invasive species introduction.

2.2 Approach

For the purpose of this power analysis, it was assumed that the baseline rate of invasive species introduction in year zero (time 0) was 5 species per year, and this rate was increasing log-linearly at a rate of 0.05 per year. It was further assumed that monitoring occurred annually for 20 years. The number of invasive species detected per year, under different detection probabilities (ranging from 0 to 1, in 0.05 increments), was estimated. The rate of change in detections was assessed using a generalised linear model (GLM). If this model identified a statistically significant increasing trend (effect size = 0.05, level of significance (alpha) = 0.05) then this was determined to be a 'success' (i.e., the number of detections increased in line with the number of introductions). This process was repeated 1000 times for each detection probability. The number of successes (statistically significant positive trend output from the GLM) was recorded and used to determine the power of detecting a positive invasion trend (e.g., if 600 of the 1000 iterations successfully identified a significant trend then the power is 60%) for a given probability of detection.

2.3 Outputs

The power to detect a positive trend in invasive species introductions increases as the probability of detecting the invasive species increases. However, the relationship between detection probability and statistical power is non-linear, such that the increase in statistical power slows at higher detection probabilities, in particular, detection probabilities above 60%.

Under the power analysis assumptions (see approach), to detect a positive invasive species invasion trend at least 80% of the time, a detection probability of 0.55 or greater is required. The minimum detection probability required to achieve greater than 95% power is over 0.9 (Figure 3). These outputs highlight the importance of designing a monitoring programme to achieve a high detection probability, for example, by increasing method sensitivity, the number of sites sampled, and optimising the sampling approach according to the site risk distribution (see simulation outputs above).

This power analysis provides valuable insight into the ability of a monitoring programme to detect a change in the rate of invasive species introduction; however, not all relevant aspects could be explored by this simple analysis. Importantly, this analysis assumes that a species introduced in one year can only be detected in the year of introduction. It was not possible to account for the cumulative probability of detection in subsequent years and the influence this would have on the

ability to detect trends. Additionally, this analysis examined only a single assumed effect size (i.e., the rate of change in introductions). This single effect size allows for comparison between different detection probabilities; however, statistical power is expected to be greater for larger effect sizes and lower for smaller effect sizes. Similarly, statistical power is likely to be lower for detecting a decreasing trend in the introduction rate when this rate is close to zero, due to the asymptotic nature of rates close to zero.

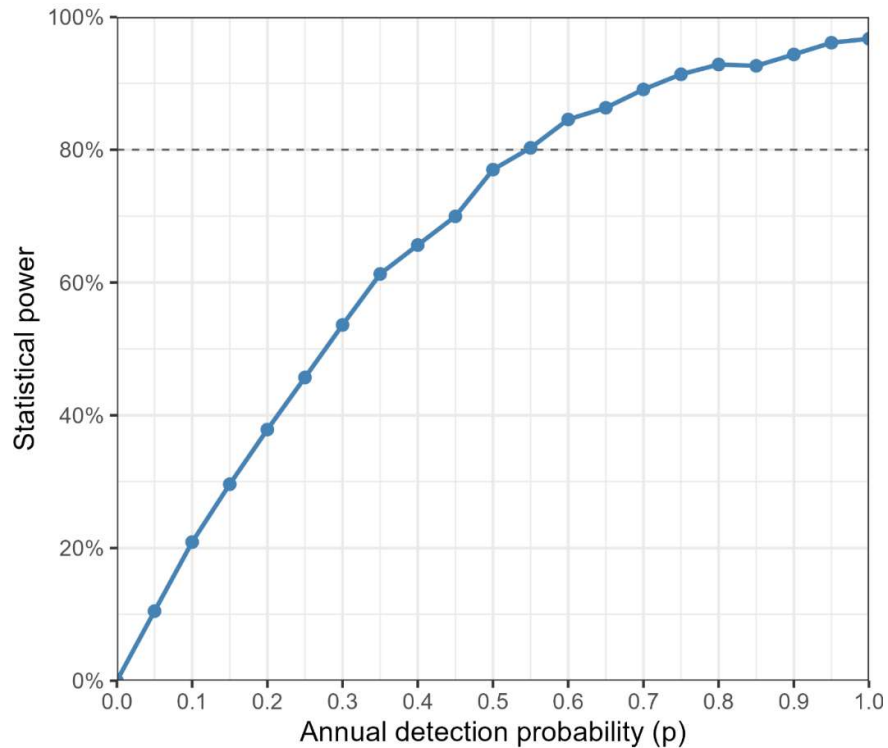


Figure 3. The statistical power of a monitoring programme according to its detection probability, where the statistical power reflects the percentage of simulations for which a statistically significant positive invasion trend was detected.

3 References

Gibson, T. I., Millard, R. S., MacMillan, I., Taylor, N., Thrush, M., Tidbury, H. (2025). Application of a theoretical simulator to the optimisation of risk-based invasive species surveillance. *NeoBiota*, 97. <https://doi.org/10.3897/neobiota.97.121188>