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Deliverable 4.2 Novel technologies for biodiversity monitoring - Final Report

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EUROPABON

Final Report

Novel technologies for biodiversity monitoring

Deliverable 4.2

Lead beneficiary: European Commission

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Deliverable description	Final report detailing the approaches and findings from WP 4.2 on the assessment of novel biodiversity monitoring techniques
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Executive summary

The goal of this task was to identify and characterise novel methods for biodiversity monitoring, and to assess their suitability for large scale deployment across Europe. To address this goal we combined extensive literature searches with expert consultation, namely using a survey and through an online workshop. The outcome of our searches is summarised in a metadatabase, which includes 282 methods or method components, which have been classified according to EBV classes addressed, target taxa, and broad method type the method relates to. We then consulted experts within the EuropaBON network and beyond, on the advantages and challenges associated with each of these novel methods, as well as their technology readiness level. In combination, our approaches revealed a wealth of novel methods and a highly active research field, with extensive emerging innovation on several fronts. However, it also revealed high variability in technology readiness, with lack of validation being a prevalent hurdle yet to be overcome for many applications of these methods (i.e. for some taxa and in some environments). Moreover, the opportunities for expansion in observations created by these novel approaches open new challenges associated to the standardisation, integration and storage of biodiversity monitoring data. Finally, the expansion of observations should take a designed approach, in order to deliver on its potential to improve representation and resolution of biodiversity monitoring, and should aim to complement rather than replace human observations.

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Section 1– Task overview

Work Package 4 (WP 4) in EuropaBON aims to co-design a biodiversity monitoring workflow for Europe after assessing user and policy needs (WP 2) in parallel with assessing existing biodiversity monitoring workflows and their bottlenecks (WP 3). Task 2 within WP4 (WP4.2, hereinafter as "task") is focused on identifying and analysing novel methods, method components, and technologies (these are defined in Section 2 below; hereinafter as "methods") for filling existing gaps in biodiversity monitoring. In addition to summarising these emergent methods and technologies, this task has also evolved to include a critical assessment of the methods and technologies for their suitability and potential implementation.

1.1 Task objectives

1. Identify and systematically characterise emergent/novel methodologies, method components, and/or technologies for monitoring biodiversity according to criteria including but not limited to method readiness/maturity, methodology type, taxonomic applicability, addressed Essential Biodiversity Variables (EBVs), and spatiotemporal coverage
2. Assess whether identified novel methods are suitable and ready to implement in EuropaBON's biodiversity monitoring workflow co-design
3. Identify areas in biodiversity monitoring that are not appropriate for novel methods

1.2 Targeted task outcomes

1. Filterable metadatabase on identified emergent/novel methodologies, method components, and/or technologies
2. Final report

We completed the majority of the first task outcome via a broad metadata search on novel methods in the first reporting period, from February to August 2021. From August 2021 onwards, we focused on meeting the second and third objectives of conducting a critical assessment of novel methods. We consulted relevant experts through a virtual Zoom workshop and discussions that took place over three days in May 2022.

Section 2– Task approaches

The task began with objective 1 to identify and systematically characterise emergent and novel methods. We conducted a broad literature and metadata search online, which was structured with the following working definitions.

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2.1 Definitions

Novel/emergent: Not yet widely applied in biodiversity monitoring, regardless of when proof of concept was published or otherwise released

Monitoring methodology: a defined plan that describes data collection, processing, analysis, and in some cases, synthesis, that reflects scientific rationale and fits the targeted spatiotemporal and taxonomic scope of a monitoring goal. Methodologies typically consist of multiple components.

Monitoring method component: a defined set of steps for data collection, processing, analysis, or synthesis. Multiple components combine to make a methodology.

Data synthesis: the integration of separate datasets conducted across various locations and time points to obtain an overall signal or trend in an EBV.

Under these definitions, we move from understanding monitoring methodologies as surveying/sampling/generating data and EBV metrics into a full pipeline that encompasses data collection, processing, analysis, and synthesis, resulting in final desired metrics (**Figure 1**). Thus, novel and emerging developments in any of these steps within a methodology can be considered to improve biodiversity monitoring efforts, which includes modelling methods and databases.

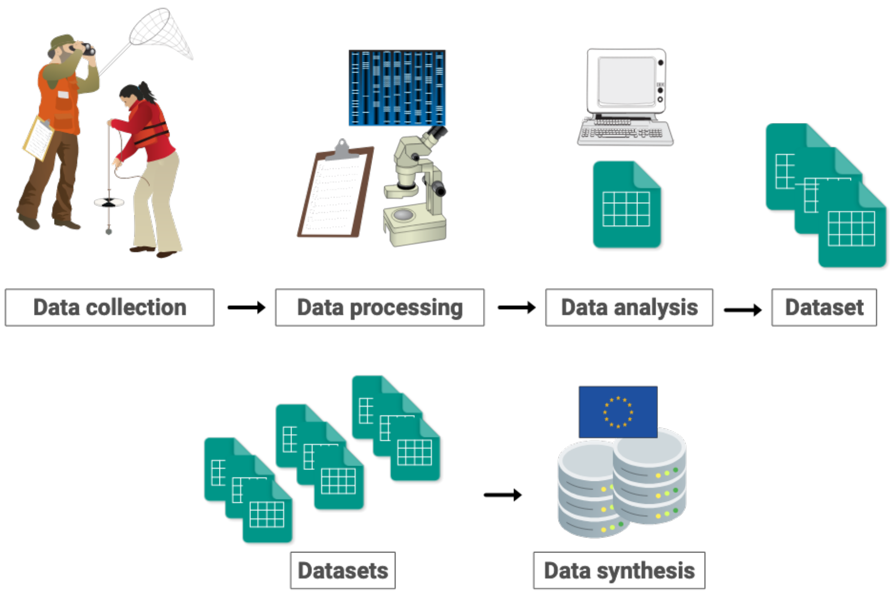

Figure 1: Conceptual figure of a biodiversity monitoring methodology pipeline consisting of four method component stages: data collection, processing, analysis, and synthesis. *Some methods may combine data collection with processing in one step, like in situ counts, but other methods like eDNA require further processing to obtain counts.*

2.2 Broad novel methods search and metadatabase

We conducted a broad metadata search across recent scientific literature and websites, such as industrial/commercial websites, maker space communities, startup company websites, and PhD project advertisements. Tailored searches were conducted iteratively for each EBV class after broad searches to ensure that we attained a comprehensive and representative coverage of emergent methods.

We developed a classification structure to systematically characterise identified methods. Methods for data products and research are often expressed only in free text, and this structure serves as metadata for each identified method example. This involved creating controlled vocabulary categories for methods (e.g. remote sensing, eDNA, automated sampling, AI processing, trait databases, etc.) and attributing the monitoring bottlenecks that methods could address (from data collection to data synthesis and modelling). Where data was available, we also noted the spatiotemporal scope and resolution, target taxa/habitat, and whether methods have been validated against existing methods. Each record in the metadatabase reflects a distinct methodology. While we recognise that there will be overlaps between method components within method types (e.g. bioacoustic method components), we did not seek to merge any records together based on methodology similarity unless shared methodology with other literature was explicitly stated by authors. The outcome of this first objective is a filterable spreadsheet with 20 metadata fields on 282 examples of novel method components and technologies spanning from ecological modelling methods to portable in situ DNA barcoding (**Table 1**). Section 3 below covers the trends and findings on the novel methods identified.

2.3 Expert consultation

Following our search for novel methods and technologies, we consulted expert opinion through surveys and a virtual workshop to critically assess suitable novel methods for implementation in EuropaBON's biodiversity monitoring workflow. We first used the compiled methods metadatabase and the EuropaBON member network to identify relevant experts as target invitees from October 2021 to February 2022. We then designed and broadcasted a survey based on our metadatabase structure through EuropaBON's communication channels and the Consortium's network to complement our broad method search to mitigate any gaps or blind spots. We also intended on using the responses from the surveys as a starting point for workshop discussions. While the uptake for these surveys was not as high as intended (total of 25 responses from 16 experts), we began the majority of our virtual workshop planning in early 2022.

The primary aim of our workshop was to bring experts together from research, technology, and biodiversity monitoring coordinating bodies to identify and assess novel methods and technology so that we can understand what method components can be practically implemented and what gaps remain. We designed a short virtual workshop that spanned three days in 90-minute sessions. Although our workshop was open for registration from anyone, our advertisement strategy for this workshop included both targeted invitations to identified experts and a public broadcast (**Figure 2**). We extended invitations to 67 experts

Table 1: Novel methods metadatabase structure. *All novel method records in our metadatabase are systematically characterised according to the following metadata fields. They are detailed below according to their field data type (controlled factors, free text, or binary).*

Metadata field	Field type	Description
Method name	Free text	Descriptive name of method
Source URL	Free text	URL of website describing method. DOI links where possible.
Source origin	Free text	Description of how this method source was found
Method component	Controlled factors, multiple allowed	Methodology component: collection, processing, analysis, synthesis, whole pipeline (falls in all 3 categories)
Method type	Controlled factors, multiple allowed	AI, Automated sampling, Bioacoustics, Camera trap, Citizen science, Data scraping, Data transfer, Database, eDNA, Genetics, Isotoping, Modelling, Photogrammetry, Remote sensing, Sensor network, Software/package, Telemetry
Development stage	Controlled factors, multiple allowed	Developing, proof of concept, used in research, in use.
Estimated cost	Free text	Cost of apparatus or method if provided.
EBV class 1	Controlled factors, multiple allowed	Top level of EBV classes that describe biological level: Genetic composition, Species populations, Species traits, Community composition, Ecosystem functioning, Ecosystem structure
EBV class 2	Controlled factors, multiple allowed	Level 2 of EBV classes nested within each class listed in EBV class 1: Community abundance, Ecosystem distribution, Ecosystem disturbances, Ecosystem phenology, Ecosystem Vertical Profile, Effective population size, Genetic differentiation, Inbreeding, Interaction diversity, Intraspecific genetic diversity, Live cover fraction, Morphology, Movement, Phenology, Physiology, Primary productivity, Species abundances, Species distributions, Taxonomic/phylogenetic diversity, Trait diversity
Input data type	Free text	Input data type required for this method
Output data type	Free text	The output data type as a result of the method. This can be a biodiversity metric or data product for further downstream use.
Target habitat	Free text	Method's target habitat, or if this is not defined, what the data recorder interprets as an applicable habitat for the method.
Target taxa	Free text	Method's target taxa, or if this is not defined, what the data recorder interprets as applicable taxa for the method.
Validation	Binary	Whether the method has been validated positively with conventional widely used methods
Temporal resolution	Free text	Includes unit of time. Smallest capable unit of data collection.
Temporal extent	Free text	Includes unit of time. Furthest capable time scale of data collection, if applicable.
Spatial resolution	Free text	Includes unit of area. Smallest capable area of sampling.
Spatial extent	Free text	Includes unit of area. Farthest capable area of sampling.

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Figure 2: Example of social media graphics used in our public broadcast strategy with Pensoft to advertise the expert consultation workshop.

and monitoring programme coordinators in total representing a range of expertise across taxa, habitats, and various EBV classes. We also wrote a Contribution and Attribution Policy (**Annex A**) based on the CRediT contributor roles taxonomy (https://credit.niso.org/). This policy outlines how contributions in the workshop could be reflected in acknowledgments and co-authorships in publication outcomes from this task. We ensured that all involved EuropaBON partners and workshop participants were given the opportunity to provide their feedback and agreement to this policy. During registration, participants were also given an option to register their interest in joining the Consortium as co-authors in our review manuscript preparation (targeted outcome 3).

A total of 218 individuals from 36 countries were registered for the workshop, and approximately half of the registrants also registered an interest in being contacted after the workshop to serve as co-authors in our upcoming publication. Out of those, 218 individuals registered, 110 individuals attended at least one workshop day session from May 11-13, 2022.

We hosted this event with technical support from the Marine Alliance for Science and Technology Scotland (MASTS). Jessi Junker (iDiv MLU), Daniel Kissling (UvA) and Miguel Fernandez (iDiv MLU) gave introductory talks on the EuropaBON co-design task and EBVs to the workshop attendees on Days 1 and 2, respectively. The majority of the workshop session was centred around breakout rooms, where experts were grouped either by taxa expertise (Day 1) or EBV class expertise (Day 2). Within each breakout room, we used a visual collaboration board platform, Miro (http://miro.com), to structure and capture discussion outputs (**Figure 3**). Discussion aims for the first two days consisted of:

Day 1-2 discussion aims

- Identify novel methods and technologies (not yet widely used in monitoring) for each taxon group (Day 1) or EBV (Day 2)

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- Classify methods by technology readiness levels (see below)
- Assess each method's main advantages and disadvantages
- Understand implementation and infrastructure needs

Importantly, we asked participants to utilise an adaptation of the NASA Technology Readiness Scale to assess biodiversity monitoring methods/technologies in our breakout rooms (**Figure 4**). This scale improves on our metadatabase structure ranking and also incorporates information on validation, which we expressed only as a binary value. The NASA Technology Readiness Scale contains levels from 1 to 9 with three broad readiness categories: research, development, and deployment (NASA 2021). While NASA defines validation as proof of function, the focus of our workshop, like our broad method search, centred around validation of novel methods against conventional methodologies (e.g. whether remotely sensed trait diversity aligned with conventionally measured trait diversity). In addition to focusing on identifying suitable technologies, we also asked participants to discuss more broadly the gaps in infrastructure that need to be addressed if such a technology were to be implemented widely.

Our discussions on Day 3 focused more on this high-level aspect, where participants were asked to summarise common themes and gaps they identified across the first two days of the workshop.

Day 3 discussion points

- What points over the past two days do you think require particular emphasis in our co-design of monitoring workflows?
- Are there common themes you have noticed in terms of practical needs for implementing suitable novel methods?
- What gaps in biodiversity monitoring remain that cannot be addressed by novel methods yet?
- Are there reasons (e.g. sociological impact) we shouldn't automate/reduce in-person observations in biodiversity monitoring?

Consortium partners involved

In addition to the lead institution for this task, USTAN, the following EuropaBON Consortium partners were involved in the preparation and operations of this expert consultation workshop. Members at Pensoft assisted with the communications and social media strategy related to the event. iDiv MLU members provided technical support for event details and registration through EuropaBON's email lists, newsletter, website, and member portal system. IIASA supported the workshop through management of the Miro platform and served as discussion moderators. Other partners also involved in the workshop delivery include iDiv MLU, CIBIO, UREAD, NIVA, CREAF, and UvA. The team members at USTAN sought technical support from within their institution for the virtual Zoom delivery of the workshop from MASTS. All Consortium members from the above listed partners are named accordingly in our Contribution and Attribution policy for their roles.

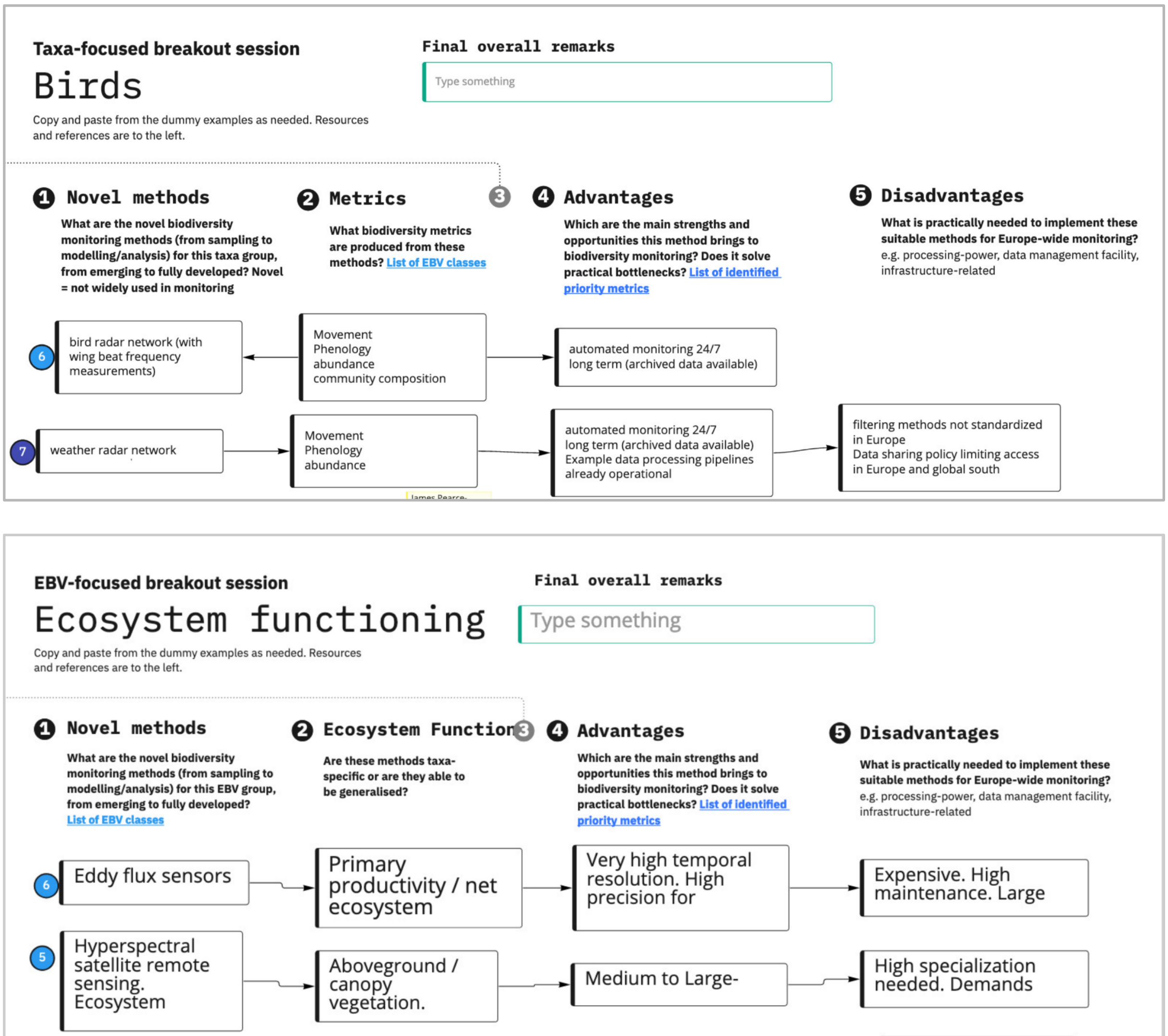

Figure 3: Miro visual collaborative boards for breakout discussions. *Example screenshots of the collaborative boards used to capture input from workshop participants. The layout is an adaptation of the discussion aims for days 1 and 2 based on taxon grouping (above) and EBV grouping (below).*

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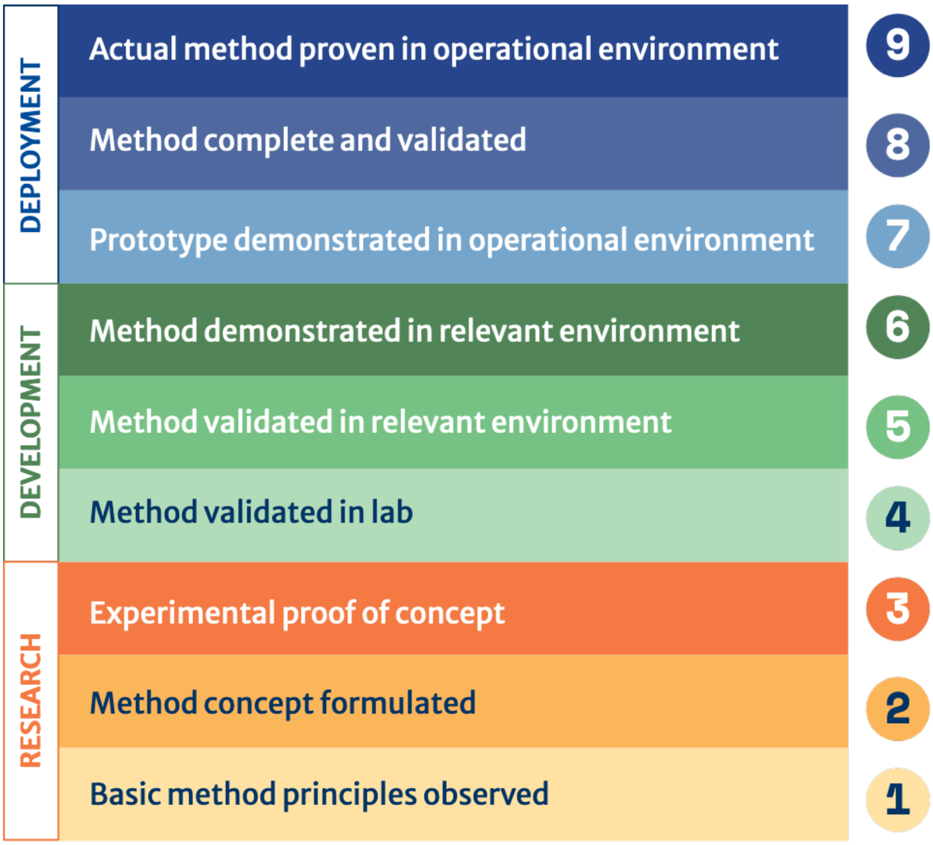

Figure 4: Adapted NASA Technology Readiness Scale. *The NASA Technology Readiness Scale quantifies the readiness of a technology in levels (technology readiness levels, TRL, 1-9) from basic proof of concept to the final stage of a technology being tested and validated in its success. These levels fall under three overarching categories of research, development, and deployment. We adapted the wording from NASA to fit monitoring methods (Source: NASA, edited by Tzinis 2021; https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level).*

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Section 3— Trends and assessment of novel methods and technologies

In our method metadata search, we identified a total of 282 method components or methods. A majority of our records consisted of method components that addressed data collection (n = 163) which was roughly equal to the sum of all other method components (**Figure 5**). We detected similar patterns when disaggregating methods by types— databases to aid data aggregation/synthesis (e.g. trait databases) for analysis (n = 76), remote sensing technologies using unmanned aerial vehicles (UAV), LiDAR, and satellite imagery (n = 64), and AI-based analysis methods (e.g. machine learning, convolutional neural networks, etc.; n= 31; **Figure 5**). Conversely, if we assume novelty of a method type based on the number of method records, the most "novel" or least developed types for European biodiversity monitoring are photogrammetry and data transfer (satellites for telemetry monitoring). The methods most likely to be ready for implementation (defined as the number of method records and shown to be in use) were associated with eDNA, in both scientific research and commercial applications (e.g. Oxford Nanopore, nanoporetech.com, and NatureMetrics, naturemetrics.co.uk).

In terms of the EBV classes that could be addressed from our identified novel methods, an overwhelming majority was catered to quantify species distributions and abundances (**Figure 6**). Several methods were not able to be assigned to EBV classes as they were method components that were complementary and did not necessarily result in an EBV (such as cloud computing networks or AI-assisted processing). Genetic diversity, ecosystem vertical profile, and interaction diversity EBV classes were the least commonly targeted metrics in novel methods (**Figure 6**). The lack of records for these method types may be due to uncommon use as biodiversity target metrics.

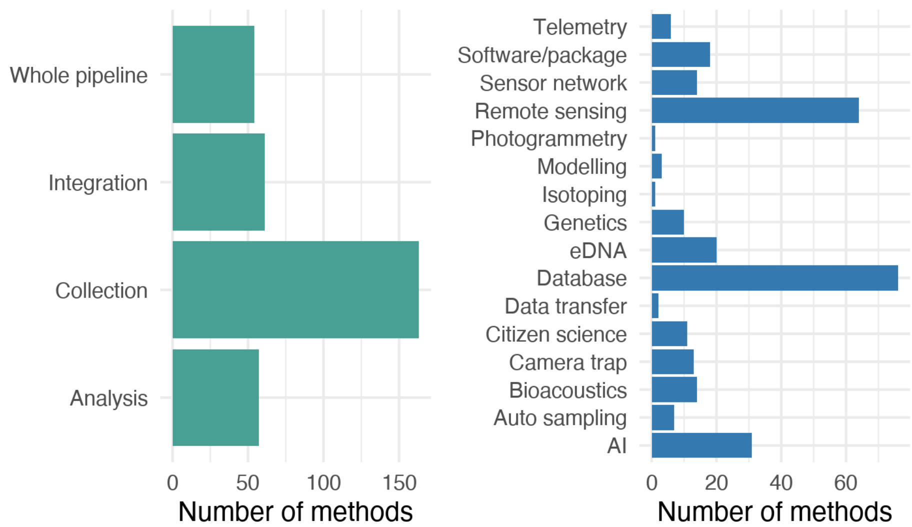

Figure 5: Identified novel method components and technologies by method types through initial broad search. *Methods (n = 282) are classified according to method component stages (left) and method types (right). For both types of classifications, method records are allowed attribution of multiple categories.*

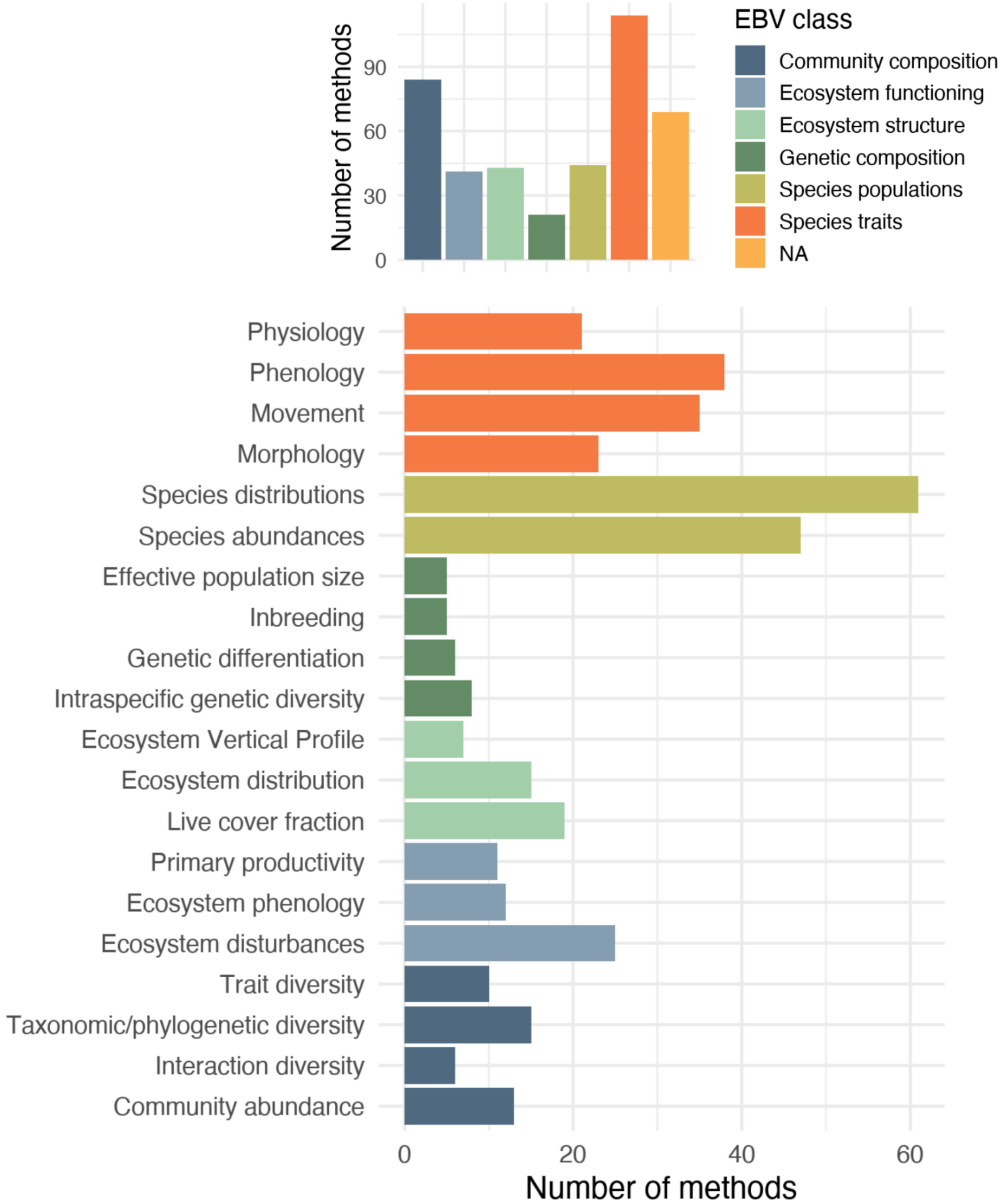

Figure 6: Identified methods through initial broad search according to potentially addressed Essential Biodiversity Variables (EBV) classes. *Number of methods according to two levels of EBV classes, the broadest according to biological level from the genetic to the ecosystem level (above, differentiated by colours), and then further EBV classes within each biological level (below).*

While the number of records may point to a well-validated method type, the quantity alone should not be indicative of the efficacy or readiness. Our team recognises that a well-designed method pipeline only needs components that are selected carefully for the right taxa and habitat. We were able to identify such components through expert consultation in our workshop.

3.1 Overall technology readiness trends

Taxa groups were highly variable in what novel methods are suitable and their readiness level. Because workshop participants were given a choice of their respective breakout sessions according to taxa and EBV classes, subscription between groups was not equal. Taxa-focused groups for terrestrial invertebrates, plants, birds, and mammals received the most expert participation, and this was reflected in the quantity of inputs captured in our Miro boards (**Figure 7**). Experts provided examples of novel methods that spanned the range of our Technology Readiness Scale. Overall, we did not find a clear pattern in any taxa group where methods tended to score a TRL 7 or above, although all taxa except algae and aquatic invertebrates had at least one method at maximum readiness level. While not significantly higher, methods for mammals tend to be better developed and more ready than others.

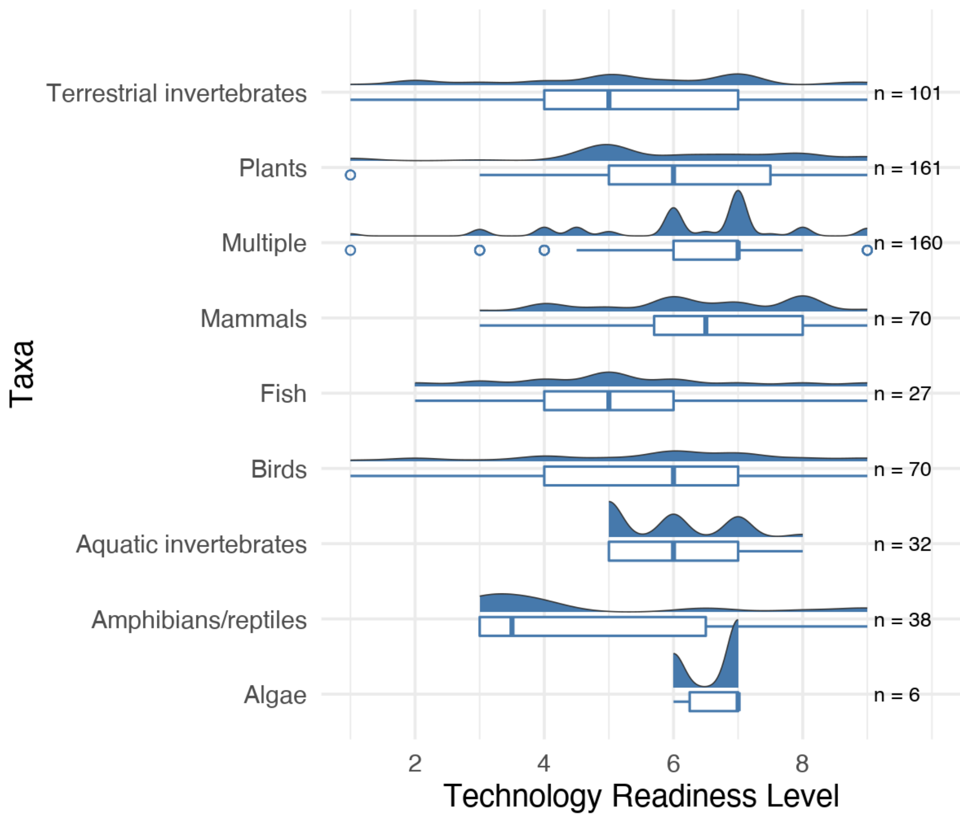

Figure 7: Expert assessment of novel methods readiness according to taxa. The technology readiness for 169 novel methods identified by experts are shown here grouped by taxa. This readiness level corresponds to an adaptation of a scale developed by NASA. Methods are allowed multiple taxa classifications. Macrophytes and fungi were omitted from this visualisation due to a lack of records.

We do however, see a clear pattern for taxa groups where implementation of novel methods is not suitable. For example, experts commented that some technologies may be presented broadly as ready for implementation, but very little validation has been done for some of the taxa considered. This is discussed more in detail below.

When disaggregating methods according to related method types and EBV classes, distributions of expert-identified methods along the Technology Readiness Scale show somewhat clearer patterns than taxa groupings. Telemetry, biologging, photogrammetry, and database method components tended to be the most ready based on their medians. Again, most methods had at least some implementations at maximum readiness level. The distribution ranges however show that readiness is spread widely for most categories with at least 10 methods. This emphasises again that methods are not consistently ready across taxa or EBV classes— readiness is highly dependent on validation, and this is likely concentrated in model organisms or systems. Remote sensing methods received the highest number of mentions/records but not in its average TRL (**Figure 8**).

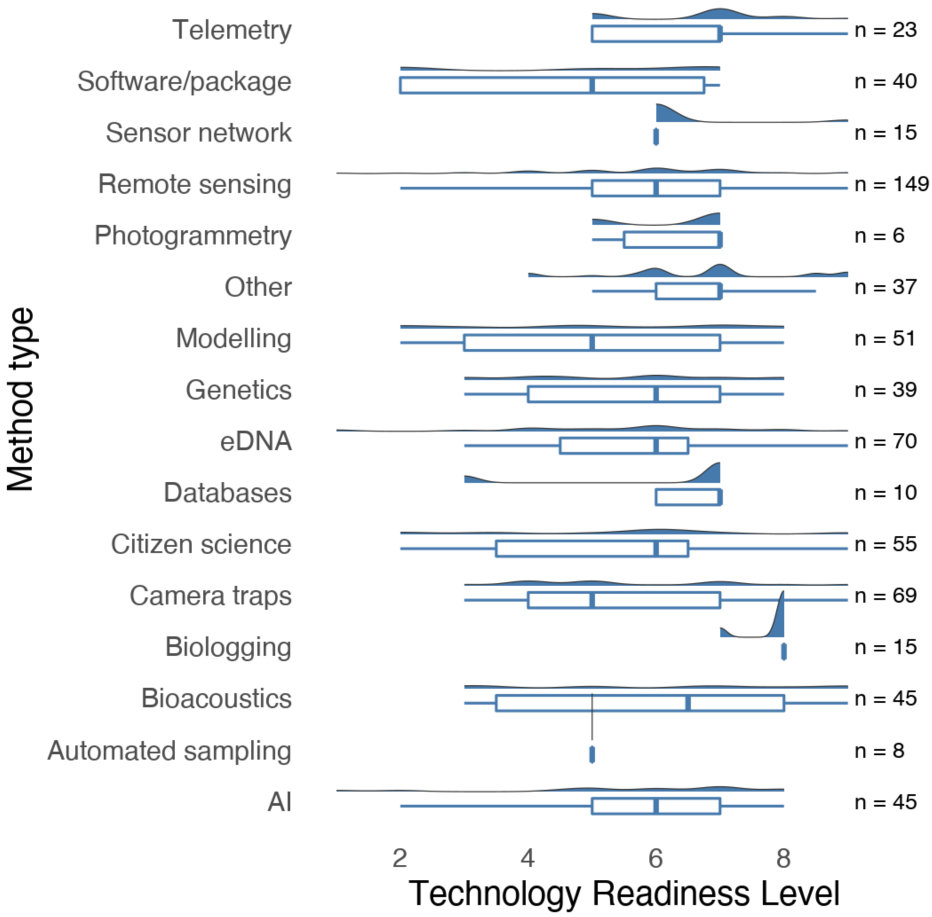

Figure 8: Expert assessment of novel methods readiness according to method type. The technology readiness for 169 records of novel methods identified by experts are shown here grouped by method types. This readiness level corresponds with an adaptation of a scale developed by NASA. Methods are allowed multiple category classifications.

eDNA was also an important category for consideration across taxa groups (**Figure 8)**. Not surprisingly, this was a prevalent novel method mentioned for EBV classes relating to species distribution and community abundance monitoring. Other EBV classes highly suited for implementing novel methods were physiology traits, movement traits, and ecosystem phenology (**Figure 9**). Some EBV classes are nested within method types. For example, telemetry and biologging are used primarily for movement tracking and spatial ecology monitoring, and so we see that methods for movement traits are similarly highly ranked in readiness (**Figure 9**). Aside from these notable EBV classes, as a whole, we do not find clear patterns based on a method type alone and so we will discuss novel methods further specific to taxa contexts.

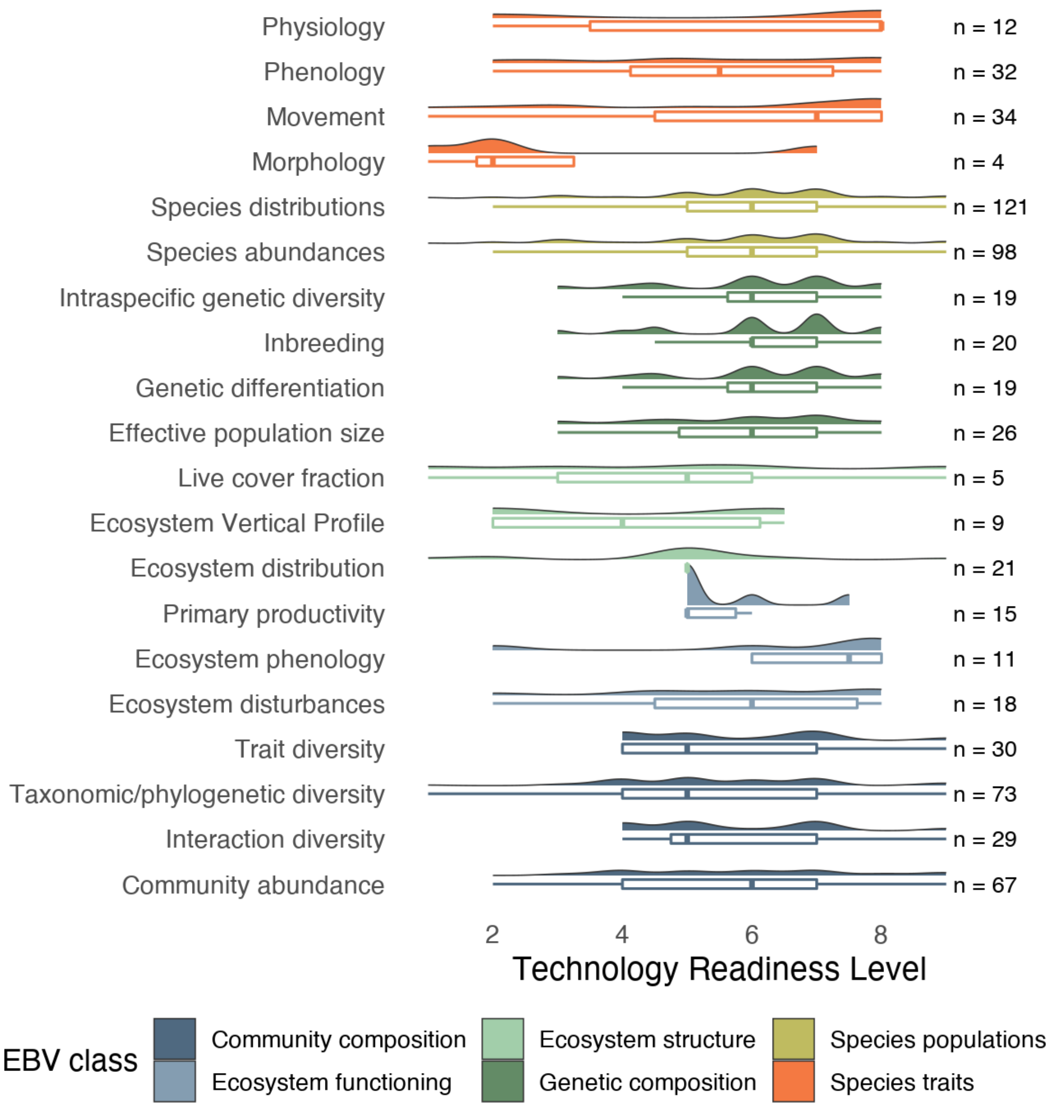

Figure 9: Expert assessment of novel methods readiness according to EBV class. The technology readiness for 169 novel methods identified by experts are shown here grouped by EBV classes. This readiness level corresponds with an adaption of a scale developed by NASA. Methods are allowed multiple EBV classifications.

3.2 Novel methods by taxa

Because discussing method suitability and readiness hinges upon sufficient validation and testing relevant to taxa groups, we will discuss expert assessments of novel methods within taxa groups. All inputs from experts in taxa-focused or EBV-focused days are included here. The following sections will detail EBV classes, suitability, advantages, and disadvantages.

Amphibians and reptiles

As detailed above, novel methods for monitoring amphibians and reptiles were amongst those that ranked the lowest in their technology readiness, largely due to the need for validation and testing. eDNA was the only method type or component identified as a particularly suitable novel method for amphibians. eDNA has yet to develop to quantify species or community abundances, but it has clear advantages to understand species distributions for priority indicator species. Experts noted the potential in adapting conventionally used methods in mammal monitoring for amphibians and reptiles, like camera traps that employ thermal imaging. However, there are taxa-specific concerns like ectotherm detection that make this difficult. Passive acoustic detection, potentially combined with AI to identify species abundances based on mating calls, was the most suitable and mature method assessed. Experts did note that to do this passively at scale would require implementation of a strong information technology structure to integrate such a volume of data.

Aquatic invertebrates

All identified novel methods for aquatic invertebrates by experts were given a TRL of 5 and above (i.e. at minimum, the method was validated in a relevant environment). The most highly ranked methods related to eDNA-based metabarcoding. Disadvantages inherent to eDNA and metabarcoding were listed for these, such as the lack of abundance data and limited double use for community and genetic diversity. However, eDNA-based methods lend a significant advantage in reducing processing labour, especially regarding taxonomic error and resolution. Experts did note during plenary discussion that aquatic and terrestrial invertebrate monitoring are highly disconnected, despite several insect groups that have aquatic life stages. Established reference libraries and training datasets to serve as taxonomic standards may be key to bridging this gap.

Birds

Novel biodiversity monitoring methods for birds were amongst the most varied. EBV classes were largely focused on migration/movement monitoring, community composition, species distribution, and species abundances, and several highly ranked methods addressed all these EBV classes. We recognise that bird monitoring has had a strong history in involving citizen scientists, but making data more structured and usable in analysis and synthesis has been a recent focus in research and was assessed as the most ready method component, with clear advantages demonstrated in large monitoring programmes with the aid of mobile smartphone apps (eBird, ebird.org; Pan-European Common Bird Monitoring Scheme, pecbms.info). However, this contrasts with data sourced through citizen science in an unstructured manner, which cannot adequately address rare species monitoring and also requires more elaborate analytical/modelling techniques (such as combining with AI-based verification) to account for potential biases and unequal sampling effort. Other notable emergent methods mentioned for birds were related to remote sensing via weather radar networks (BirdCast, birdcast.info) and bioacoustics. Long-term automated monitoring was possible by utilising weather radars and data processing pipelines exist with sufficient demonstration of functionality. Bioacoustics, on the other hand, still requires complementary methods developed to better model abundance and increase species recognition breadth (e.g. BirdNet, birdnetpi.com). As a whole, the disadvantages for novel bird monitoring methods all involve how to navigate data synthesis and analysis through modelling and/or data aggregation. However, this issue has been proven to be navigable by leading programmes and organisations listed above. Bird monitoring does not appear to have data collection issues, but clear challenges are present in analysis and synthesis with such high volume.

Fish

Currently, a large proportion of fish biodiversity monitoring relies either on fishery-dependent techniques like trawl surveys or, less commonly in Europe, in situ diver surveys. Experts identified 10 novel methods with potential for application in scalable monitoring of fish, all of which focused on non-destructive techniques. They fall under five broad types: eDNA, AI-assisted video/camera surveys, bioacoustics, remote sensing, and telemetry tags. Methods that ranked high in TRLs were echosounder survey methods and tagging, either acoustic or satellite. Both are strong examples of the extremes and trade-offs in scaling up monitoring efforts. Echosounder surveys can give biomass estimates through the water column for a large area but cannot provide species resolution, while tagging provides high resolution data on a few individuals and is difficult to scale due to the cost of tags and intensive data processing. Methods marked as the most nascent were eDNA for genetic diversity and species abundances and remote sensing of low trophic level aggregations (e.g. bait balls). While they share advantages with other methods like reducing collection effort, experts believe much more validation work needs to be done. eDNA for community diversity, on the other hand, is ready and well-validated. Experts did note that proper standardisation and reference libraries, like those mentioned above, are needed, and moreover, there will not be abundance or size structure information.

Mammals

Mammal monitoring has also had a strong history as an early adopter of novel methods, such as camera traps and biologging. For this taxa group, some of the most highly ranked methods were improvements upon these technologies especially in expanding measured EBV classes: AI-assistance to analyse camera trap data and later generation developments on biologging. Beyond a “tried and true” use of camera traps for species or community distribution and abundances, experts also added that collection of trait data like phenology, physiology, and morphology are emergent. Other highly ranked methods were bioacoustic monitoring for vocalising species, such as bats, eDNA via faecal samples, and AI-verification of citizen science data in smartphone apps (iMammalia, european-mammals.brc.ac.uk). Some methods mentioned only for this taxa group were UAV monitoring of aggregations or colonies, which are well tested in very specific groups like seals at known haul-out sites, and using municipal road-kill data as a complement to modelling. Detection dogs were also suggested as a way to navigate detectability bottlenecks, especially for more cryptic or rare species, but this requires high-level training and does not reduce surveying labour as much as other methods might. Expensive costs and training investments were the most often cited drawback by experts.

Plants

For plants, expert input focused largely on terrestrial implementations. Remote sensing was a dominant method type suggested by experts. 22 out of 38 novel methods (57%) applicable to plants related to remote sensing, especially in LiDAR which were the highest ranked in technology readiness. Not surprisingly, the main advantages in remote sensing make it possible to monitor ecosystems at large ecosystem scales. This method also spans several more EBV classes than any other novel method type, spanning species distributions of invasive species to ecosystem functioning and services. Current satellite imagery, UAV technology, and LiDAR improvements combined with tailored modelling techniques make this method a “multi-use” component, in which a single data stream can be analysed differently in modelling for different EBV classes (e.g. for ecosystem cover, primary productivity, species traits, trait diversity, etc.). We also find this to be an advantage based on our broad method search, in that most validation examples come from vegetation remote sensing studies. However, remote sensing heavily favours canopy vegetation, and few methods were able to address monitoring of the understory assemblages. Some notable novel methods mentioned that were not given TRL rankings but addressed less “common” EBV classes were eDNA approaches to understand pollinator-plant interactions, eDNA pollen sampling from air, and proximal sensors (“leaf clips”) for trait diversity measures. Aquatic plants received fewer inputs, but experts similarly suggested eDNA monitoring and remote sensing to understand the species and community level EBVs.

Terrestrial invertebrates

Expert input on terrestrial invertebrates primarily focused on insects, targeting the taxa group according to movement modes: flying and ground-crawling insects. The most highly ranked novel methods identified by experts were adaptations on automated imaging and recognition and trapping techniques. While automated imaging and species recognition could massively increase spatial sampling effort, taxonomically comprehensive and precise training data/reference libraries remains the biggest barrier to scaling this method at present. An example of this technology deployed and operational is a network of automated camera traps paired with AI species identification in the Netherlands (Diopsis, diopsis.eu). Secondly, experts identified two novel adaptations of trapping techniques: SLAM Traps (Sea, Land, and Air Malaise traps) and pheromone trapping. SLAM traps reduce surveying efforts and could potentially be combined with DNA metabarcoding to also reduce data processing needs. Pheromone traps operate similarly using targeted pheromones for single species monitoring, which can be useful for priority species. Experts do note that both methods have yet to be tested at scale, but the use of molecular methods in SLAM traps can reduce taxonomic bias and error, which is an issue key to entomology. Other notable novel methods applicable for spatial and temporal scaling are bioacoustic monitoring of vocalising insects with high potential to engage citizen scientists and using entomological radars to understand the abundance of large migration groups. Weather radars used previously for bird monitoring are also being developed for insect monitoring, but this is still emergent.

3.3 General remarks and conclusions

We dedicated our third day in the expert consultation workshop to allow experts to discuss general needs or concerns after two days of focused inputs. Even though we centred discussion around four core questions on novel biodiversity monitoring methods, similar themes occurred throughout:

- Need for standardisation in data collection and data infrastructure,
- Importance of infrastructure, especially for data storage and sharing, and
- Gaps in reference knowledge/databases

First of all, experts overwhelmingly emphasised the need for standardisation throughout the entire methodological pipeline. Data collection, if it is to increase spatial scale, requires coordination and proper standardisation across member states, not only to ensure data interoperability but also to prevent misuse of resources through redundant or overlapping efforts. The strength of biodiversity monitoring, unlike scientific research, lies in longevity and consistency, and standardisation is key to ensuring usability of data across geographic locations. Standardised data collection methods also secondarily aid highly specialised techniques in data quality control and training surveyors. Coordination is imperative in both conception and execution of biodiversity monitoring, and this has previously been done unidirectionally, from monitoring organisations like OSPAR or the European Bird Census Council or through policy directives like the Water Framework Directive. The co-design aspect in EuropaBON can establish standards for monitoring methods and achieve this with a clear vision from data collection to synthesis.

Furthermore, implementing some of the identified novel methods at scale will likely increase data storage and computational power requirements. Investment is needed for storing memory-heavy data, such as images, audio, videos, as well as storage of data products. The co-design of biodiversity monitoring workflows should not only define the novel methods to implement but also establish the necessary supporting data infrastructure best practices and standards. Many experts noted that using common data and metadata standards like FAIR Data Principles, GBIF's Darwin Core, and Dublin Core standards would be an important first step. Common data standards can then also mobilise older data so that previous monitoring datasets containing baseline information can also be integrated (e.g. eLTER, ICOS, LifeWatch). One expert also pointed out that if citizen science participation is to be integrated extensively, especially using mobile and portable devices, considerable efforts are required to ensure data privacy in raw data like audio or images.

For many novel method components that are almost fully ready for deployment, comprehensive reference databases are a final missing piece for data analysis. One that experts consistently mentioned were reference libraries/databases for eDNA, metabarcoding, and AI-based methods. While these types of methods were some of the highest rated by experts for each taxon group, centralised references are core to powering their automation or interpretation potential. This will also be a crucial link to validate taxonomic knowledge with molecular data. Fields like insect monitoring will rely heavily on a comprehensive library in order to resolve closely related species if eDNA or metabarcoding methods are to be used more widely. Centralising references will also mitigate biases while standardising data processing pipelines. This, again, would be one upfront investment in establishing monitoring infrastructure. One such effort currently underway by ARISE is a central data annotation and AI training module with ecologist and AI expert inputs.

Reasons against methodological change

Lastly, in our assessment of innovation in monitoring methods, we also found several reasons against methodology change. Several identified method components are simply not ready to be deployed at scale and more development needs to be done prior to committing to methodological change. Specifically, many method components discussed above were lacking validation relating to our target taxa groups and habitats. One expert noted that if EuropaBON and the EU Commission are committed to developing specific novel method components that further funding should be made available for validating methods past proof of concepts. This is also necessary so that existing time-series data from long-term monitoring can still be used in analyses and syntheses. While there are a myriad of novel method components that are ready and well-validated, for many, the need for more validation studies is the primary reason to not switch to more novel methodologies at present.

Similarly, some EBV classes inherently involve manual searches and surveys that cannot be automated or replaced with technologies, such that the costs in developing novel method components would be similar to investing in in situ observers. Experts agreed that EBV classes related to reproduction traits and population demographics for many taxa are not likely to be replaced by novel technologies, especially if they require methods like recognising bird rings, searches for nests/dens/etc..

Species identification also remains a large hurdle for many automation attempts even if training data are available. Beyond establishing automated identification with existing taxonomic knowledge, experts also asked about how the field would solve the issue of keeping up to date with the dynamic nature of taxonomy. This would also be a critical downside to using novel method components for rare species monitoring, given that rare species would have a much lower volume of existing data for references and training datasets. Experts were also aware that novel methodologies could unintentionally “lock in” previous biases and errors particularly for taxonomy, and any automation system should have an auditing mechanism to avoid this phenomenon.

Furthermore, there are additional costs to automated sampling or monitoring beyond direct apparatus costs. While our expert consultation was not able to provide concrete costs, experts cautioned that automated networks would not be the ideal “hands-off” reality promised in practice, because deploying a network of automated monitoring devices still requires infrastructure for maintenance. These devices will continue to require in-person presence, and should maintenance lapse, devices can also become pollution sources through batteries and sensors. Experts also note that even if the benefits outweigh maintenance costs, European countries will likely vary in their ability to afford these costs on a long-term basis. Any novel method component proposed as a change to monitoring programmes should factor in this aspect so as to avoid sampling biases associated with wealth. A consensus emerged in the workshop that novel methodologies should supplement rather than replace in situ observations for both scientific and sociological reasons. First of all, removing in field observers eliminates all unplanned observations/discoveries, which are critical to detecting precursors of disturbance or change. For scientists, unplanned discoveries are important for generating new knowledge and research questions, but within monitoring, unplanned observations can also signal a need for adapting monitoring programmes. Monitoring programmes need clear objectives and outlined targets at inception, but they should also be allowed to adapt, especially if surveyors detect changes in ecosystems that do not fall within the monitoring targets. Surveys in the field thus also act as a feedback system to monitoring. Sociologically, disconnecting researchers from the field potentially could affect how scientists communicate value to the wider community. Maintaining a physical link plays a key role in how we value our ecosystems and communicate these values to new generations of scientists, general public, and stakeholders. Experts advocated for novel method components to be used to expand observations where they were suitable but cautioned against losing advantages from in-person observations.

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Section 4— Key takeaways

In summary, our review and workshop have uncovered a wealth of proof-of-concepts and research literature on novel biodiversity monitoring methods. This is a very active research field, with innovation progressing on multiple fronts. However, the technology readiness level of methods is highly variable. Most methods, most taxa and most EBVs have at least some method components at the highest levels of readiness. Yet, methods that are fit for purpose, i.e. validated with more conventional methods and tested for target taxa/habitats, are in the minority. Furthermore, we find novel methods ready for implementation favour the scale extremes for EBV classes: either specialised high-resolution data for a restricted group/area (e.g. animal-borne tagging on a few individuals) or large-scale coarse level data (e.g. species present in a region). After assessments across taxa and different EBV classes, method components that integrate remote sensing, structured citizen science observations, and eDNA appear to be the most ready to adapt for some of EuropaBON's monitoring needs across Europe. Our work here consisting of a broad method search and expert consultation shows that science and industry are moving monitoring technologies and methods forward across several disciplines. In doing so, opportunities for data collection are expanding, creating new challenges related to data storage and integration. Moreover, this expansion of observations provides a critical opportunity to improve efficiency, representativeness, spatial and temporal resolution. To achieve this potential, more development is needed in data synthesis and standardisation within (in some cases already existing) monitoring methodology pipelines to scale monitoring Europe-wide. Experts also advised several areas of emerging challenges in methodological change. For taxa or EBV classes where methods are mature and ready, scaling monitoring will likely accumulate costs toward infrastructure requirements, especially for data storage and apparatus maintenance. A biodiversity monitoring workflow scaled up for long-term efforts across Europe can realistically integrate novel method components, and our task here defines the potential to and practical considerations needed in EuropaBON's co-design efforts.

Annex A

Contribution and attribution policy

The EuropaBON consortium members involved in *Work Package 4.2: Novel biodiversity monitoring methods and technologies* ("we") aim to publish a review paper as an outcome of the Method Assessment Workshop. Before the workshop begins, we want participants to be made aware that their inputs in session discussions may be disseminated through these channels. The consortium members recognise that this output is made possible by contributions from both the consortium members and workshop participants, and as such, all contributors should be attributed appropriately. EuropaBON consortium members and participants involved in the Method Assessment Workshop will be held to follow the acknowledgement and co-authorship policy outlined in this document based on the CRediT scheme.

CRediT – Contributor Roles Taxonomy

According to the CRediT creators, science outputs result from 14 tasks outlined below. Those that we find relevant to the review paper are bolded for emphasis. Please note that for the purposes of our review, the discussion taking place in the Workshop is regarded here as Investigation.

1. **Conceptualization:** Ideas; formulation or evolution of overarching research goals and aims.
2. **Data curation**: Management activities to annotate (produce metadata), scrub data and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later re-use.
3. Formal analysis: Application of statistical, mathematical, computational, or other formal techniques to analyze or synthesize study data.
4. **Funding acquisition:** Acquisition of the financial support for the project leading to this publication.
5. **Investigation:** Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection.
6. Methodology: Development or design of methodology; creation of models.
7. **Project administration:** Management and coordination responsibility for the research activity planning and execution.
8. **Resources:** Provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools.
9. Software: Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components.
10. **Supervision:** Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team.
11. Validation: Verification, whether as a part of the activity or separate, of the overall replication/reproducibility of results/experiments and other research outputs.
12. **Visualization:** Preparation, creation and/or presentation of the published work, specifically visualization/data presentation.
13. **Writing (original draft)**: Preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation).
14. **Writing (reviewing and editing):** Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre- or post-publication stages.

Co-authorship

We believe co-authorship requires a significant contribution towards at least 3 out of the CRediT's 14 roles. We lean towards authors inclusion and believe that anyone who has contributed significantly to 2 of the first 12 roles should be offered the opportunity to contribute towards writing the paper. Particular care should be taken in providing opportunities to contribute to early career researchers. We believe that discussion of co-authorship should take place early in the research project and that transparent agreements are beneficial to both the people involved in this review and the EuropaBON project. **Please contact EuropaBON (info@europabon.org) if you did not see the option to opt-in to serving as co-author when registering for the workshop.**

Acknowledgements

If there are workshop participants and consortium members that have contributed to these CRediT roles but not sufficiently for co-authorship and/or declined to participate as a co-author, EuropaBON consortium members leading the writing of the report deliverable and review paper should attribute their contribution in the acknowledgements.

Role contribution

This section lists the EuropaBON Consortium individuals involved in this Task (Table 1) and their contribution to the CRediT roles outlined above (Table 2).

Table 1. Individuals involved in EuropaBON Task 4.2

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Table 2. Individual contributions to EuropaBON Work Package 4.2 according to CRediT roles: Conceptualization (C), Data curation (D), Funding acquisition (F), Investigation (I), Project administration (P), Resources (R), Supervision (S), Visualisation (V), Writing original draft (W1), Writing reviewing and editing (W2). Roles which have not yet taken place but are anticipated to be completed are shaded blue.

Name	C	D	F	I	P	R	S	V	W1	W2
Maria Dornelas	x		x		x	x	x		x	x
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Robert Patchett	x	x			x				x	x
Daniel Kissling	x		x		x		x		x	x
Henrique Pereira	x		x		x	x	x		x	x
Jessica Junker	x		x		x	x				x
Tom Breeze	x								x	x
Pedro Beja	x		x		x				x	x
Anne Lyche Solheim	x				x				x	x
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Ian McCallum						x				x
Hannah Ladd-Jones					x	x				
David Paterson						x				
Francisco Moreira	x								x	x
Leonard Sandin	x								x	x
Laurence Carvalho				x					x	x
Martin Musche				x					x	x
Marit Mjelde				x					x	x

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