2 Monitoring as a field

Anna Allard, Claire Wood, Lisa Norton, Andreas Aagard Christensen, Veerle Van Eetvelde, Alan Brown, Henrik Persson, and Louise Eriksson

Introduction

This book describes examples of biodiversity monitoring, focused on land and oceans. There are many ways of collecting data, and researchers constantly find new ways of making technology work for their purposes, influencing the development of new approaches to monitoring. Monitoring can be very important to highlight the effects of policies, especially where they may have potentially harmful impacts on nature. We encourage students to do a thorough research of current monitoring before embarking on any new monitoring schemes, in order to identify any existing monitoring, even monitoring that uses different or older methodologies.

This book aims to capture the monitoring process, starting with the need for information (often driven by policy), framing questions that could be answered by monitoring and then identifying approaches for finding answers to those questions. One important aspect of deciding on monitoring approaches is when to choose a particular type of data collection and how to combine different datasets to produce data that can help in decision making. This may include understanding the role of humans in driving change in ecological systems. In our modern world, so many different types and scales of evidence are available, from the observation of a lichen on a tree trunk to the flow of debris following a Saharan sandstorm across the world (seen in near real time by an orbit of satellites). This chapter provides a basis for understanding different monitoring approaches.

Biodiversity monitoring

The definition of *biodiversity monitoring* in this book comprises an interdisciplinary field that includes both environmental and social science. Its focus is to protect Earth's environment and human health by sustainable management and conservation or restoration of natural resources. Although we are well aware that other areas exist, such as the monitoring of atmospheric layers, weather monitoring in relation to climate change, or monitoring for security or response to emergencies, those are not included in this book. Also not included is the type of biodiversity research involving the capture of organisms, seeds, and fragments of plants swirling in the air together with insects, which constitute a lot of biodiversity dispersal on local to global scales. The rich biodiversity below ground is only touched upon in the form of environmental DNA (see chapter 8).

Our scope encompasses more than just the actual collection and evaluation of data or their potential use in forecasting, as mentioned in the European Union (EU) definition (European Environment Agency 1999). It also includes the importance of understanding

DOI: 10.4324/9781003179245-2

social and political drivers of biodiversity change. Governments tell us that biodiversity monitoring is needed to benefit society by helping to maintain *public goods* or *environmental services*, and this need comes out of a recognition of unwanted and damaging environmental change from pressures on land use, the exploitation of resources, pollution, and climate change; see chapter 3. Monitoring can show how the health of the environment is intimately linked to the health of society and can be an appropriate response to local concerns from people who will be affected by a deteriorating environment and will benefit from its restoration. In this sense, environmental protection will have many clients, including future generations (United Nations, Economic Commission for Europe 2016). In a wider setting, biodiversity and environmental monitoring often need to be a part of a programme of policy, funding, and practical measures to maintain and restore threatened environments.

Types of monitoring

As a baseline, the type of monitoring approach you need to adopt depends on the questions that you need to answer. Do you have a clear question? Are you collecting data to answer some future question? Or are you just curious and testing to see how the data you collect will enhance your knowledge associated with your interest (see Table 2.1)? Commonly, biodiversity applications can include work in the field of archaeology (see more in chapter 8). Though including broader social science is even less common, this book illustrates how to build bridges between social science and monitoring for policy and interdisciplinary research.

Curiosity driven

Curiosity-driven or passive monitoring typically has no statistical design and is not linked to answering specific questions or triggering any particular management intervention, with no requirement for reporting. The effectiveness of this type of monitoring depends on the knowledge and motivation of whoever is carrying it out. For example, a site manager might use a monitoring scheme to learn about the long-term changes on their site as a way of structuring what would otherwise be ad hoc observations or a way of gaining enough ecological understanding of change to specify a more focused hypothesis-driven scheme. To qualify as monitoring, we suggest there would have to be enough specification (what, where, and when to observe or record) so that the same scheme could be carried out by another observer to give important information about trends. Trends, for example, are possible increases or declines in populations or habitat diversity and what changes may have occurred in spatial patterns and distributions (e.g. Lindenmeyer and Likens 2018; Ten et al. 2021).

Mandated monitoring

Mandated monitoring is carried out in response to the requirements of government legislation or directives (such as the EU Habitats Directive; European Commission 1992); for example, monitoring of resources of great economic importance such as national forest inventories. There are usually some general specifications on what habitats, species, or environmental measurements to include, often leaving the details of sampling design and methods to governments or regional agencies. Here it is appropriate

Table 2.1 Some monitoring types and some of their uses

Monitoring type	*Who monitors and how*	*Who wants the result*	*Who else benefits*
Curiosity driven	Varied, depending on the nature of curiosity	In many cases the one who does the monitoring; for example, researchers testing a hypothesis or ecologists using old maps to investigate ruined or abandoned homesteads to find cultural biodiversity	The results of the curiosity-driven investigations often put thoughts into the minds of others (members of the public, politicians, or scientists) and become the start or pilot case of a mandated monitoring scheme.
Mandated	Typically, they are large-scale. Universities, science centres, or consultancy companies usually run the monitoring.	Authorities, for use in planning environmental management and reporting data higher up in some obligatory chain of reporting	The results are useful for settling disputes or driving opinions to be considered in political decisions in conflicts of interest; for example, land use in forests as industrial timber farming or recreation and berry picking.
Question driven	As in mandated, often done by researchers etc.; usually smaller scale. Pilot cases of regional or local scale. Looking to answer specific questions, with a scheme designed accordingly.	For quantity data, to answer questions of *what is there*, *how much*, and *where*. For quality data, such questions as *who owns the land in question*, *how do they use it* and *what are their plans for it*, or *how do they cope with current regulations*?	The planners of large-scale management, in the sense of *what* and *how much* but also in the sense of *how a current situation has developed*. Research into possible future *scenarios* and insights into how to make a desired outcome feasible
Citizen science driven	Run by researchers etc.; volunteers collect at least one data source	Commonly used in many environmental settings, especially for species monitoring. In many cases, these are question-driven and/or mandated but also occur as curiosity driven.	Being involved increases people's awareness of an environmental issue, which often influences the political willingness to preserve or protect. Reduces the cost of data collection and a larger dataset can potentially be collected.
Community driven	A specific community is carrying out the data collection, often in communication with a university or consultancy company.	The community is asking for the results.	The results are of benefit in mediating conflicts between different interests.

to be aware of the risk of setting very broad classes etc., which will make the monitoring too general in its nature and will not answer specific questions or give information on issues of concern. Funding is normally from public money or by private enterprise as a condition of exploiting public goods or carrying out activities which might be polluting or otherwise harmful to the environment. Often cycles are set for monitoring and reporting, with an expectation that the results can be merged with those from similar monitoring projects to contribute towards a national or continental assessment of, for example, water quality or habitat condition, focusing on trends over time and whether or not the objectives of policy are being met (European Commission 2022).

Question driven

Question-driven monitoring has a rigorous statistical design that is able to answer predetermined questions or hypotheses. The specification should include an effect size (specifying the degree and direction of change that would be considered ecologically significant) and specified levels of both statistical significance and the acceptable risk that a real change of this order can, by chance, go undetected as a consequence of having only a small finite sample (statistical power). Often multiple questions are asked, and in the case of habitat and land cover/land use monitoring they may be based on a conceptual model, setting out possible transitions of a habitat from a desirable current state to undesirable future states that need monitoring (Houk and van Woesik 2013; Lindenmeyer and Likens 2018).

The term *top-down* means a mandated monitoring, where, in the case of EU Directives, each member state uses the same set of requirements to specify their own schemes. In contrast, *bottom-up* projects could address specific questions closely linked to site management decisions.

Sometimes these categories appear to overlap. The monitoring designed to understand how to proceed with site management, discussed in chapter 16, is both curiosity driven and question driven, even though these direct-response surveys can often avoid needing statistical designs. Public money will often not pay for curiosity-driven monitoring, but some important historical monitoring schemes started off as such projects or have since become historical records such as the phenological observations of Gilbert White, published in 1789 (Sparks et al. 2020). In Germany, lack of knowledge about the connections between rural biodiversity and farming practices generated the long-term project Biodiversity Exploratories (Fischer et al. 2010). A problem with passive monitoring is the risk that someone who is not an expert on the landscape or site context will mistake chance changes in the sample of observations for real changes or think that the surveyed sample represents the entire population. Of course, they may – but we need to know more to have confidence in making this inference, as discussed in chapter 4.

We need, however, to know what we are looking for, so effective mandated monitoring also needs to be question-driven. The ability to detect real change can be decided a priori, with the sample size determined after a pilot study to estimate the variance, or realized only afterwards, with the statistical power dependent on how many observations we happened to get funded. If we already know the sample size is too small to answer the question, question-driven monitoring may fall at the first hurdle. Expensive monitoring projects use sophisticated designs that maximize the statistical power for a given sample size, including unequal probability sampling, ratio and regression models, and stratification and post-stratification, notably using auxiliary variables from remote sensing; see more in chapters 4, 7, 8, and 9.

Citizen science driven

Citizen science–driven monitoring has boomed in recent years and is typically run by experts setting questions and designing the survey but with the data collection done by volunteers, many of whom themselves are experts and passionate about the subject. Examples are the United Kingdom Butterfly Monitoring Scheme (UKBMS), dependent on volunteer networks for recording the datasets, to enable the assessment of trends (e.g. Macgregor et al. 2019; van Swaay et al. 2019). Volunteers, often dedicated ornithologists, collect the data for the Swedish Nesting Bird Inventory (e.g. Brlik et al. 2021; Morrison et al. 2021); see more in chapter 6.

Community driven

Community-driven monitoring, or community-based monitoring, is a type of monitoring in which a specific community is either carrying out the data collection or driving the demand for the results (Wilson et al. 2018; Khair et al. 2021), as exemplified in chapter 17, which shows what cooperation around reindeer husbandry have achieved through innovative reindeer husbandry plans.

Quantitative and qualitative data

To incorporate social science in monitoring, other approaches are often used. Mandated monitoring, coming from an authority in response to concerns, is not always straight-forward where these concerns involve people and their use of the land, culture, and ownership (both in reality and in the sense of belonging). An alternative is to start by collecting quantitative data (information about quantities, and therefore numbers) such as *research in register data*, which is the focus of chapter 12. Monitoring in terms of human evaluation of landscapes (e.g. preferences) can be done by *surveys using questionnaires*, further discussed in chapter 13.

The other type of data is *qualitative* data, which regards circumstances that can be observed or elicited but not measured, such as peoples' sense of place (e.g. Minichiello et al. 2008). Monitoring in this regard can be done by conducting *interviews*; read more about this method in chapter 14. Approaches for taking humans into consideration, when combining social data and landscape components for evaluations of how landscape and people interact, are exemplified in Text box 2.1, and some of the main differences between the two types of data are summarized in Table 2.2.

Approaches to data collection

The key information is that successful monitoring programs are based on well-defined questions, a conceptual understanding of relevant ecological processes, and a robust study design that allows for inferences to be made about ecosystem change while also remaining adaptive to new information and questions (European Commission 2022).

It is crucial to determine beforehand whether the monitoring will be used to indicate the change between two visits (long-term monitoring) or just record the status at two points in time. The statistical inferences differ significantly between these two approaches and large-scale field long-term monitoring. Monitoring works (with a few exceptions) with what is called *uncertain knowledge*, which is solved by statistical sample design. Large sample sizes

Text box 2.1: Human evaluations of landscapes

Evaluations of landscapes may include assessments of scenic beauty – that is, the extent to which a landscape is perceived to be unattractive or beautiful – or scenic preferences, in terms of disliking or liking a particular landscape. To take this one step further, willingness to engage in different activities in diverse landscapes has been studied as a way to learn about the fit between people's activities and the features of the landscape.

An understanding of human evaluations of landscapes requires that both human and landscape components be considered. Landscape type, such as a forest or open landscape, and different characteristics including the height of trees, ground vegetation, etc., are important dimensions. In turn, people have different experiences, values, and beliefs that influence evaluations. Landscape experts (e.g., managers) but also lay people (e.g., tourists, rural and urban populations) have been studied to learn about how people assess landscapes. Overall evaluations can consider how people interact with landscape characteristics.

Elementary for an understanding of evaluations is the need to develop appropriate landscape stimuli and to use reliable measures of evaluations. Landscape characteristics need to be defined and presented in a standardized way to determine their relevance for evaluations. Photos are the most common way of eliciting landscape evaluations, but technological advances have enabled computer visualizations where landscape features can be experimentally manipulated to ensure high stimuli control. In addition, virtual reality techniques are increasingly used. Even though it is expensive to use real-world landscapes, and these enable less control over specific landscape features, such studies are characterized by higher external validity and are necessary for holistic understandings of landscape evaluations, including the role of sound and smell, for example. In addition, the scales used for evaluations require a proper conceptualization and pre-testing. Given differences between people in how they evaluate landscapes, the sample has to be carefully selected and considered when interpreting results. For an understanding of the physiological and psychological processes underlying evaluations, studies have furthermore included measures such as blood pressure and cholesterol level, as well as individuals' evaluations of the setting and the emotions a setting evokes, to enable conclusions as to why people evaluate landscapes in a certain way (Sundli Tveit et al. 2013).

Even though people evaluate landscapes differently, the methods employed to study evaluations have revealed some distinct patterns. For example, people generally evaluate forest landscapes positively if they contain many large trees of different ages and species but with sparse ground vegetation. However, there are also divergences in how experts evaluate landscapes compared to the general public (Eriksson et al. 2012). These general insights have obvious implications for policy and planning. Nevertheless, it is important to consider the specifics of a certain landscape and the people living there when using these results in practice.

Table 2.2 Some of the main differences between qualitative and quantitative data collection

Data collection	*Qualitative*	*Quantitative*
Conceptual framework	Focus on understanding human behaviour from the informant's perspective	Focus on determining facts about biodiversity or social phenomena
	Assumes a dynamic and negotiated reality	Assumes a fixed and measurable reality
Methodological framework	Data are collected through participant observation and interviews.	Data are collected through measuring, quantifying, or classifying.
	Data are analyzed by themes from descriptions by informants.	Data are analyzed through numerical comparisons and statistical inferences.
	Results are reported in the language of the informants.	Results are reported through statistical analyses.

Source: Modified after Minichiello et al. (2008).

become expensive, prohibiting detection of rare occasions; see more on design and sampling in chapters 4 and 5. Modelling the world as some part of the monitoring scheme is very common, either at the initial stage or as a stage somewhere in the chain of collection. Machine learning–based methods and, in particular, deep learning have become increasingly used in later years, and these methods require even larger amounts of annotated reference data compared to traditional model-based methods used in the past (see more in chapters 7 and 8).

There are several *scales* to consider in monitoring (e.g. Sparrow et al. 2020):

- The scale of area: from the local investigation of earthworms in a single field, a regional survey of shrub types in a county or rural patterns of housing over a cluster of counties, to a national survey of landscape classes or with an international, pan-European, or global reach.
- The scale of time: for instance, the biodiversity of pastures with different cultural histories or in stratified layers of the soil through environmental DNA, going back to prehistoric times.
- The scale of resolution: from small-scale detail, via in situ data, to the large landscape view provided by satellite data.

Types of data collection

We use different ways to collect data for biodiversity monitoring. In reality, however, most monitoring schemes use a range of different methods to achieve their goal, either as a predefined scheme or as innovative ways to complete or repeat an existing monitoring scheme and to fill in gaps of knowledge when compiling data sources. Two examples in this chapter pinpoint the wide range of different ways to collect data in the same monitoring scheme; Figure 2.1 sketches some of the ways to collect data relevant to the scope of this book.

The landscape of today is shaped by natural processes but also largely by the efforts of yesterday's inhabitants working the land. Monitoring the old landscape and the continuity

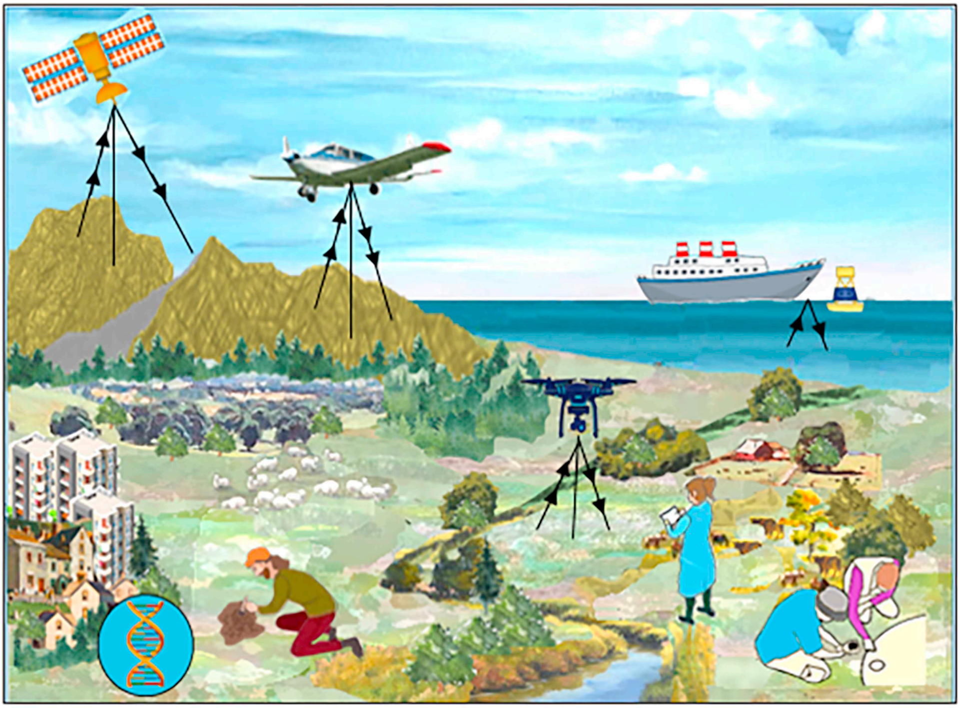

Figure 2.1 A sketch representing some of the data collection methods for biodiversity monitoring in the scope of this book, involving collection of data from many different sources and used in various ways. From social data, in registers, as understandings of human evaluations, to human use of the land, now as well as through history, and the impact it has on the ecology.

Credit: Image by Anna Allard.

of biodiversity over time is important, because the current biodiversity is highly dependent on earlier land use. Ways to monitor this include excavating the site; analysis of environmental DNA, microfossils, and pollen cores; comparing older aerial photos (often going back to the 1950s) and satellite archives (back to the 1970s); and interpreting old maps, some of which go back to the 1600s. The discipline of historical ecology and research across time using aerial photos are introduced in chapter 5.

In situ data collection

In situ data collection can be stand-alone, taking up the entire monitoring effort, but most often constitutes only a part of the whole setup, which combines the simultaneous use of traditional field observations and samples observed with innovative new technologies. Leading the way for others are the large intergovernmental monitoring networks around the oceans, which have enormous setups of in situ measurements to complement remote sensing and fill gaps in knowledge needed to provide analyses, modelling, and forecasts. Examples are the Baltic Marine Environment Protection Commission or the Helsinki Commission (HELCOM) and the OSPAR Commission, an intergovernmental cooperation to protect the marine environment of the North-East

Atlantic (HELCOM Baltic Marine Environment Protection Commission 2022; OSPAR Commission 30th 2022). Many types of devices are employed: buoys, sea vessels, autonomous floating platforms, sea floor capture, drones, trailing or drifting devices with multi-sensors, tide gauges – even sensors on marine mammals. They record such things as bio- or geochemical measurements (chlorophyll or sediments in water), nutrients, salinity, and temperature, from the surface all way down to the sea floor (e.g. Merchant et al. 2019; Sastri et al. 2019; Wang et al. 2020; Programme of the European Union 2022).

Some variables must be collected in the field, such as single species of plant or fish, investigating the finer details of soil profiles or water, or searching for archaeological and historical clues; see more on in situ monitoring in chapter 5. This type of data also makes up *ground truth*, meaning the data used in computerized classifications or models, either as training or for validation of the product afterwards (Cavender-Bares et al. 2022); see chapter 9. Field surveys can be very labour-intensive: a survey of lowland Wales (Stevens et al. 2004) took over a decade to complete and at the time was regarded as too expensive to repeat. However, remote sensing now makes it possible to adapt surveys as a baseline for monitoring, making it easier to survey both points and areas for assessment, estimates, and thematic mapping – see more on this in chapter 9.

Whatever the type of monitoring, some type of sampling design must be used, for practical reasons: working with samples and making estimates of populations is more efficient than trying to count, measure, or observe the entire population, unless we are monitoring species or habitats, with known locations to visit. The downside is that we need to follow probability-based sampling designs and use complex statistical analysis, but this is a small price to pay in the age of computers. Citizen science in some cases can make similar, representative observations based on a sound statistical design (for more on sampling design and principles, see chapters 4 and 6).

Experiments

Experiments use randomization of treatments and controls to draw conclusions about cause and effect. Some forms of monitoring and environmental impact assessment look similar to experiments, notably for stream water quality and recovery from marine pollution; for example, designs of before-after-control-impact (BACI). Though inferences from these designs can only be made with caution, they show the possibility of using "natural experiments" and controls to suggest causal mechanisms for changes in biodiversity (Hurlbert 1984; Underwood 1992; Stewart-Oaten 1996; Filazolla and Cahill 2021).

Habitat surveys

Habitat surveys are common as a way of finding out what the resource is and where. Land cover and land use surveys have a long history of answering the questions of *how much of a given resource or environmental service is there, and where do we find it?* Some of the early surveys were not designed to be repeated and often used interpretative field methods without fixed points, which could be revisited. However, the national monitoring schemes typically use layouts specifically designed to be repeatable, enabling the important possibility to add the question*: Is there any change?*

Satellite remote sensing has a different approach to data collection, aiming for frequent, complete spatial coverage, known as *wall-to-wall*, rather than observing only a scatter of points or small sample areas every few years. Remote sensing observations still have uncertainty but it is less the result of sampling choices and more to do with correction factors for atmospheric conditions and limiting spatial, spectral, and radiometric resolution. Because these sensors in effect see everything visible from above, there is also uncertainty around separating out variables of direct interest from all of the other factors that influence the way light is reflected (see more in chapter 7).

Early satellites for vegetation monitoring often covered the Earth at rather long intervals (e.g. the Landsat missions, U.S. Geological Survey 2022), the weather satellites have always made frequent overpasses but with pixel/raster sizes on the kilometre scale (e.g. National Oceanic and Atmospheric Administration 2022). Images had to be purchased from an archive or specially "tasked" and substantial funding was required to use satellite data. During the last decade, many more satellites, carrying optical instruments as well as radar and laser sensors, have covered the surface. Satellite imagery and archives of algorithms and scripts used for analysis now can be accessed freely on global cloud-based platforms together with compiled maps (e.g. phenology or grasslands), such as Google Earth Engine or the EU Copernicus Services giving access to the Sentinel satellite complex, of optical multispectral and radar data. Recent years have seen a policy shift into making maps and data as open source, downloadable for use, allowing them to be integral parts in planning or finding possible sites for selected habitats; see examples in chapter 8 or the maps and data of the UK Countryside Survey in this chapter (see Figure 2.4; UKCEH Environmental Information Data Centre 2022).

Integration of variables and scales and modelling

Monitoring often draws upon different types of data, adding images or laser and radar data from different heights, such as from drones, aeroplanes, or satellites, to the mix in order to follow different lines of enquiry. Imagery from the lower heights can be used in automated object recognition and counting but see more on drone and unmanned aerial vehicles in chapter 8. However, these images can be used in much the same fashion as field surveys, using experts to interpret them into thematic classes as a source of evidence for monitoring; see more in chapter 5. Remote sensing with active sensors (sending out and receiving answers as point clouds) such as lidar or radar makes other uses possible, including seeing the ground surface below the vegetation cover and penetrating clouds (see chapters 7 and 8).

The integration of data from soils experiments or DNA sequencing of species and the comparison with archival measurements of in situ of variables related to the ecosystems in question (e.g. from climatic or phenological data) needs to be conducted in a way that contributes towards our understanding of interactions and possible changes (e.g. Cavender-Bares et al. 2022). This is done by process modelling. Modelling is not a single method, because myriad modelling methods exist in most fields of monitoring. These include the building and analysis of mathematical models of ecological processes, including both purely biological and combined biophysical models. They can be purely analytic or used in simulations, with the aim of both understanding complex ecological processes and predicting how real ecosystems might change (Amato and Giménez 2022; Jeong et al. 2022; Priyadarshi et al. 2022).

Monitoring schemes and flexibility

Long-term monitoring might maintain unchanging classes, variables, or sampling design, which is always preferable to enable recording of the real changes happening over time, without the risk of falsely interpreting due to changes in data collection. However, many schemes have to be flexible enough to accommodate new questions asked from authorities or respond when the results indicate that the sampling has too little relevant data or the wrong variables for understanding what is happening – see more on design schemes in chapter 4.

The ways in which researchers or nations classify land and waters have often been set in tradition and are thus resistant to changes in definitions. New questions from the policy side are now changing that resistance, with the need to change the content of the classes to comply with overarching data compilations; for example, pan-European ready-made analysis layers on data portals. Because we still have to find ways to incorporate existing older data in monitoring and to compile several data sources into something new, answering new or changed questions is a task that most long-running monitoring programmes will encounter. This means that there will be gaps in knowledge, and innovative ways of filling these gaps are integral to many monitoring schemes, as you will see in several chapters and examples throughout the book. There are also legacy datasets in the form of thematic maps, dividing the area of interest into units labelled with habitats, land cover, or land use. Remote sensing imagery can also be classified into thematic maps, which may be less reliable than field surveys but are typically more repeatable and have more information about spatial and thematic variation inside each classified polygon (e.g. Congalton et al. 2014).

Regardless of the choice of classes, the data collected at different scales, in the field, near the ground by drones, or at height from aeroplanes or from space all have different possibilities. The details at ground level must be translatable to the life forms at the landscape scale of the survey from above, where we see the structure and texture and use ecological skills to translate these to vegetation associations. When monitoring comprises all of these levels, measuring them in a way that makes translations possible will greatly benefit the results; a closer look at these issues is taken in chapters 8 and 9.

Accommodating the views of different stakeholders can introduce some level of ambiguity in requirements for monitoring. For collection of data, however, one is dependent on clear, unambiguous decisions on limits and content of classes as well as exactly how to collect them. This is important for repeatability, to be able to record in a similar fashion across time, across nations, or across persons doing the collection; see Table 2.3 and example on the EU level in chapter 3. Even with clear and concise instructions, any differences of interpretation between the people making *in situ* observations must be addressed and calibrations of person-to person variations is crucial to the quality of the data, see more on that in chapter 5.

Example: monitoring biodiversity in the UKCEH Countryside Survey

The monitoring work in the Countryside Survey includes many of the elements of monitoring taken up in this book. It provides a unique and statistically robust series of datasets, consisting of an extensive set of repeated ecological measurements at a national scale. It was first undertaken in 1978 to provide a baseline for ecological and land use change monitoring in the rural environment of Great Britain, following a stratified random design, based on 1km squares. It is a national-scale long-term monitoring programme, carried out by the UK Centre for Ecology & Hydrology (UKCEH, and predecessors), investigating stock and change of habitats, landscape features, vegetation, soil, and freshwaters. Based on repeated field surveys in 1km squares in the countryside,

Table 2.3 The differences between question versus data collection – or the *what*, *why*, and *how* of data collection

The question *perspective on monitoring:* what *and* why	*Data collection perspective on monitoring:* how
Is tolerant of more than one opinion; can be ambiguous in what to collect and monitor	Needs variables or classes that are fixed and have clear boundaries and are unambiguous
The limit of what has to be included can change, often due to new results and/or new concerns or opinions.	Needs clear boundaries and scope of the monitoring; for example, a geographical extent, a species population, or a range of habitats
Different opinions on what should be included can make the intent ambiguous.	Needs agreement regarding exactly what is included
Sometimes has to deal with opinions based on feelings (which are not always obvious) or anecdotal information	The method is designed to be shared and taken over by another person without introducing changes using numbers, text, lines on a map.
Uncertainty can be tolerated without defining it.	Uncertainty must be formally represented by statistical methods or equivalents.
Recommendations as text descriptions and perhaps maps	Results in data and analysis, some text
Tends towards uncertainty but having more realism	Tends towards certainty and over-interpretation
Needs to maintain adaptability of interpretation	Needs to maintain continuity of recording

Policies or demands from authorities tend to be vague, minimizing conflicts at the decision stage. This leaves room for interpretation at national or lower levels regarding how to define classes and crisp borders between them. Failing to create classes that can be translatable to other systems will cause problems when the analysis and gathering of estimates for reporting starts.

the generated data and maps are directed towards policy purposes and constitute an important basis for scientific objectives, because the survey provides evidence on how multiple aspects of the environment are changing over time. Other aims are the study of ecosystem services and how changes affect the economy and well-being of humans, to estimate progress against target indicators in biodiversity strategies and to provide data for the UK Government's reporting of biodiversity. Results and analyses of status and changes over time are available at the UKCEH Countryside Survey home page (2022); see Text box 2.2.

Thus, in the context of monitoring types, the Countryside Survey is both mandated and curiosity driven (Norton et al. 2012; UKCEH Countryside Survey 2022). Since 2019, the survey has moved from an approximately decadal year-long stand-alone survey to a rolling programme, where locations are monitored over a five-year period, enabling annual updates and resilience against atypical years in terms of weather and spreading resources more evenly. The Countryside Survey programme is complemented by the UKCEH Land Cover Map (UKCEH Countryside Survey 2021), a series of satellite-derived maps representing land cover across the UK, starting in 1990 and now annually produced since 2020.

The field survey sampling strategy is based on the Institute of Terrestrial Ecology (ITE) land classification (UKCEH, Environmental Information Data Centre (2022), which divides the land and water area of Great Britain into sets of environmental strata, termed *land classes*, to be used as a basis for ecological field survey (Figure 2.2; UKCEH, Environmental Information Data Centre 2022). Originally developed by the ITE in the late 1970s, the strata were created from the multivariate analysis of 75 environmental

Text box 2.2: Sampling and mapping in the Countryside Survey

*The sampling included in Countryside Survey field surveys (*Norton et al. 2012):

- 1978 onwards – Vegetation sampling using large randomly placed plots (main plots, 200m^2), which sample open areas in fields, woods, heaths and moors, and targeted habitat and linear feature (4m^2 and 10 × 1m) plots (maximum number of plots, 18,466; mean plots per square, 31; Wood et al. 2018).
- 1978 onwards – Soil sampling within the main plots (maximum number, 2614), including samples from the top 15cm of the profile for physicochemical measurements and samples from the top 8cm for invertebrates and microbiology.
- 1990 onwards – Sampling of a headwater stream (Strahler order 1e3) site within the survey square, comprising a macroinvertebrate kick net sample (Murray-Bligh 1999), preserved in formalin and returned to UKCEH laboratories for enumeration; a macrophyte survey based on the Mean Trophic Rank methodology (Holmes et al. 1999) but with an extended species list; and a River Habitat Survey (Environment Agency 2003) and accompanying physicochemical data (up to 373 of the 591 squares).
- 2007 onwards – Pond sampling (one randomly located pond in each of 260 squares containing ponds) comprising a pond macrophyte survey and accompanying physicochemical and habitat data, a new survey element for 2007.
- 1978 onwards – Comprehensive repeat field mapping of landscape point, line, and area features across each 1km square (Wood et al. 2018), including detailed mapping at the polygon level, according to the Joint Nature Conservation Committee (JNCC) Broad and Priority Habitat classifications (Jackson 2000).

variables, including climatic data, topographic data, human geographical features, and geology data into 45 classes (Bunce et al. 1996, 2007; Barr and Wood 2011). To select 1km survey sites, originally eight random 1km squares were drawn from each of 32 environmental classes, thus comprising 256 sample squares in the 1978 survey. The number of these sites increased to 382 in 1984, 506 in 1990, 569 in 1998, and 591 in 2007. The increase in the number of survey sites reflects the incorporation of the requirement for country-level reporting (not Great Britain as a whole). An increase in sites was necessary to obtain the statistical power to report results for England (since 2007), Scotland (since 1998), and Wales (since 2007) as separate entities. This also increased the number of land classes from the original 32 to 45 classes by 2007; see Figure 2.2, Table 2.4, and Text box 2.2. Text box 2.3 provides some examples of assessment of changes over time and Figure 2.3 illustrates field surveys across time and space in the UK Countryside Survey.

Mapping the landscape is important for understanding connections in nature. The UKCEH has a long history of using satellite imagery to map land cover, from the first national land cover map of Great Britain in 1990 to the current production of annual land cover maps and land cover change data. The UKCEH land cover classes are based on the UK Biodiversity Action Plan (BAP) Broad Habitats (Jackson 2000) and are

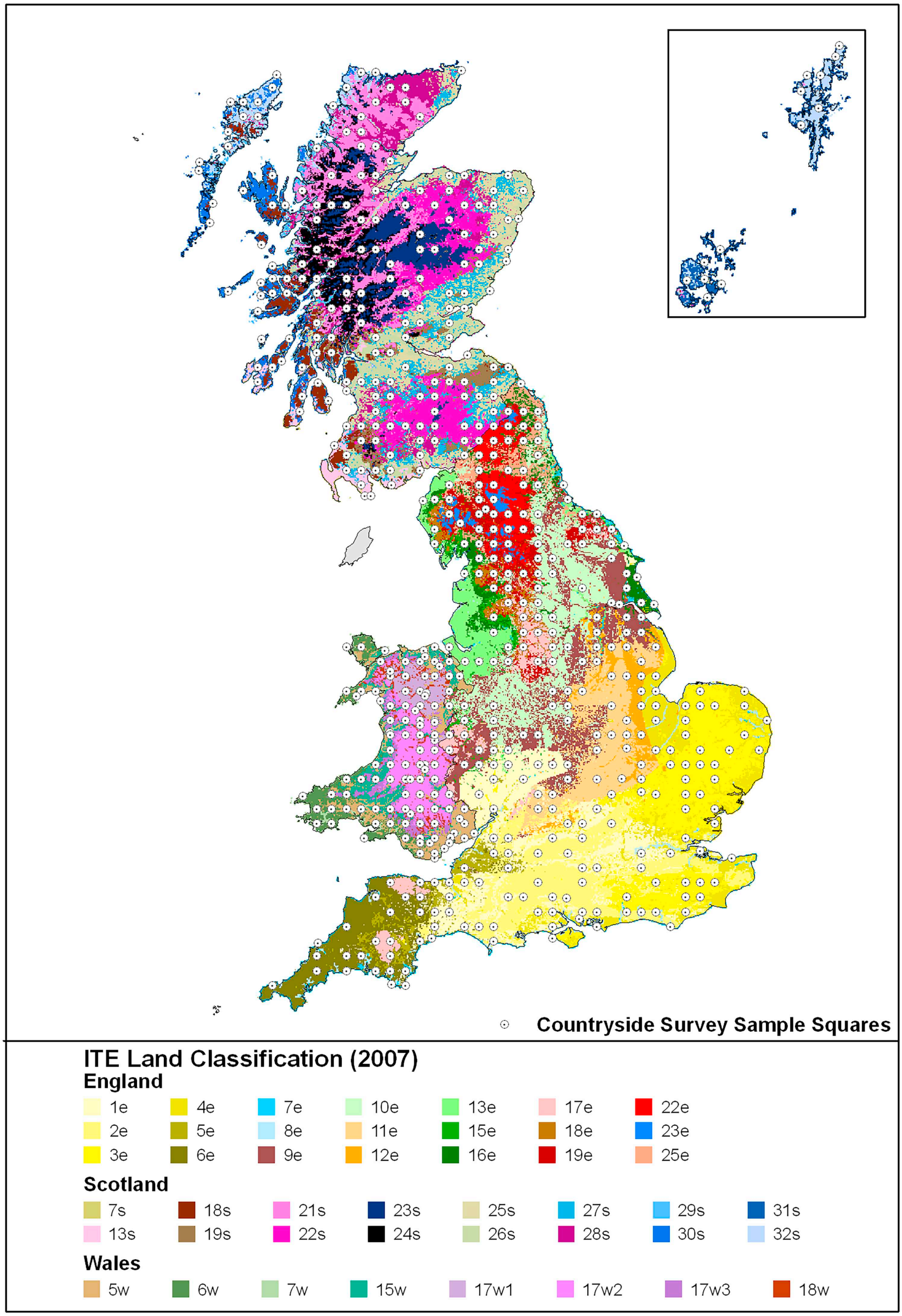

Figure 2.2 The ITE land classification and the sampling strategy for the Countryside Survey.

Table 2.4 Summary of the 45 ITE land classes, 2007 version

England	
1e	Flood plains/shallow valleys, S England
2e	Low calcareous hills/variable lowlands, S England
3e	Flat/gently undulating plains, E Anglia/S England
4e	Flat coastal plains, E Anglia/S England
5e	Shallow slopes/flood plains, S-W England
6e	Complex valley systems/table lands, S-W England
7e	Sea cliffs/hard coast, England
8e	Estuarine/soft coast/tidal rivers, England/
9e	Almost flat plains, N Midlands, NE England
10e	Gently rolling/almost flat plains, NE England/N Midlands
11e	Flat plains/small river floodplains, E Midlands
12e	Large river floodplains, flat plains, margins, E Anglia
13e	Coastal plains/gently rolling low hills, NW England
15e	Flat river valleys/lower hill slopes, NW England
16e	Gently rolling low hills/flat river valleys, NW England
17e	Upland valleys/rounded hill sides, England
18e	Upland valley sides/low mountains, N England
19e	Upland valleys/plateau's, N England
22e	Intermediate mountain tops/broad ridges, N England
23e	High mountain summits/ridges, N England
25e	Flat/gently undulating river valleys, N England
Scotland	
7s	Hard/mixed coasts, S-W Scotland
13s	Coastal plains/soft coasts, S-W Scotland
18s	Isolated hills/mountain summits, W Scotland
19s	Upland valleys/low mountains, S Scotland
21s	Low mountain slopes/upper river valleys, Highlands
22s	Round mountains/broad upper ridges, S Scotland/Highlands
23s	High mountain summits/ridges/valleys, Highlands
24s	Steep valley sides/intermediate mountain tops, W Highlands
25s	Undulating plains/gently sloping valleys, E Scotland
26s	Flat plains/gently sloping lowlands, central & S Scotland
27s	Low hills/undulating lowlands, Scotland except W
28s	Shallow valleys/low hill plateau's, throughout Scotland
29s	Inner rocky/mixed coasts/complex topography, W Scotland
30s	Outer rocky/mixed coats/low hills, W Scotland/Islands
31s	Rocky/mixed coasts/low hills, N Scotland/Islands
32s	Shallow hills/complex coastlines, N Scotland/Islands
Wales	
5w	Shallow slopes/flood plains, Wales
6w	Complex valley systems/table lands, Wales
7w	Sea cliffs/hard coast, Wales
15w	Flat river valleys/lower hill slopes, Wales
17w1	Low mountain ridges/valley slopes, N Wales
17w2	Rounded mountains/scarps/upper valleys, mid/S Wales
17w3	Variable landforms of hills/low mountain, Wales
18w	Upland valley sides/low mountains, Wales

Text box 2.3: Examples of assessments of changes over time and basis for research

- Changes in the area and distribution of broad habitats including some habitat types of special interest (e.g. hedgerows, arable field margins, and upland heath).
- Changes in the condition of habitats, especially changes in biodiversity.
- Determination of how the countryside's natural resources respond to changes in land use, climate change, and government policy.
- Updating biodiversity indicators, such as UK Priority Habitats, plant diversity (specifically open habitats, woodlands, and boundary habitats), ecological impacts of air pollution (specifically areas affected by acidity and nitrogen), invasive species, and river quality (biological and chemical).
- Changes in catchment land use – the effect on ecological quality of watercourses, their biodiversity, and ecosystem function and the effect of riparian corridors on aquatic communities.
- Ecological quality – detection of differences between ecological quality in agri-environment land and the wider countryside.
- Impacts of declines in arable weeds and butterfly and bird food plants and loss of pollinators.
- Changes in types, quantity, and distribution of non-native plant species.
- The relationship between the soil microbial diversity and soil quality; the first country-level (England, Scotland, Wales) soil sampling was carried out in the 2007 survey.
- Changes in soil acidification.
- Impact of air pollution, such as nitrogen deposited from the atmosphere, as contributing to the recorded vegetation changes.

available as both raster and vector products for the whole of the UK; see Figure 2.4. The utilization of satellite data for mapping and modelling increases as they become available (Henrys and Jarvis 2019). Also, there is now the possibility of public involvement, in the shape of the interactive modelling and finding one´s own niche, searching for those places that potentially have a favourite landscape type or contain habitats that include our favourite flowers (Henrys et al. 2015; Smart et al. 2019).

Classifications of ecosystems into habitats develop over time, and though the field survey habitat mapping component of the Countryside Survey and the satellite-derived UKCEH Land Cover Map both use classifications derived from the JNCC Broad Habitats (Jackson 2000), a new hierarchical classification system is now available. The UK Habitat Classification (UKHab) is designed to be compatible with all major classifications in use in the UK and Europe and also to large-scale geographic information system (GIS)-based habitat datasets, such as the UKCEH Land Cover Map, which provides a huge advantage for scoping large-scale surveys and for sharing data regionally, nationally, and internationally (UKHab 2022).

No single monitoring scheme, however, can accommodate all information needed for every level of detail, and as in most other countries, a series of bespoke monitoring schemes (rare plants, birds, butterflies, etc.) are carried out across the UK, depending on

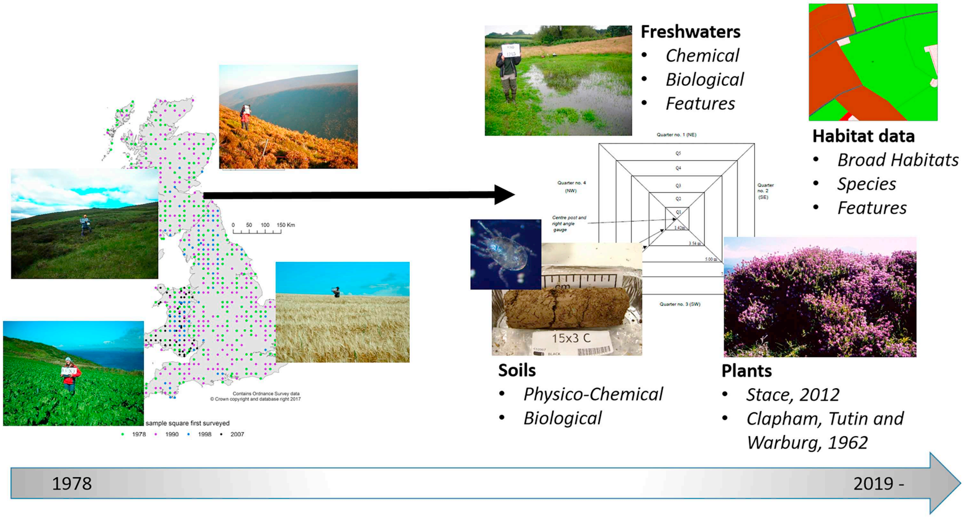

Figure 2.3 The UKCEH Countryside Survey field survey across time and space.

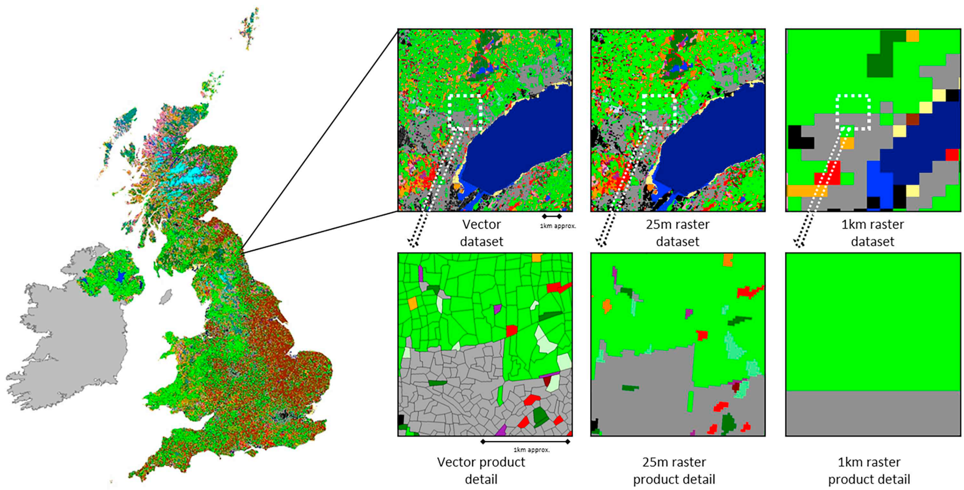

Figure 2.4 The UKCEH land cover map, 2020 (left), showing different levels of detail (right).

Source: UKCEH Countryside Survey (2021). Based on Land Cover Maps 2020 and 2007 © UKCEH 2021. Contains Ordnance Survey data © Crown Copyright 2007, Licence number 100017572.

the level of detail needed. For example, there is a complementary relationship between these general classifications used for land cover across the whole country and a second set of vegetation classes, the National Vegetation Classification (NVC), which is used by the nature conservation agencies for more detailed recording of biodiversity on protected high value sites (Rodwell 2006; JNCC 2022).

Example: high-resolution monitoring of the Belgian coast

As with many other coastal areas, the Belgian coast is vulnerable to impacts of climate change. The Climate Resilient Coast Project (CREST) ran from 2015 to 2019 (Flanders Marine Institute [VLIZ] 2022), aiming to understand local patterns of deposition and erosion of beaches as a combination of processes by waves, tides, sediment transport, wind, and human activities, using in situ measurements and related data acquisition, modelling, and monitoring techniques (Monbaliu et al. 2020).

The primary objectives were to:

- Gain a better understanding of nearshore and onshore physical processes including improved models and the validation of *grey* (not covered by vegetation) data about coastal dynamics.
- Determine the resilience of the natural coastal system (dunes and beaches) in relation to storms and wind.
- Validate calculations using state-of-the-art models, based on laboratory tests and field measurements.

To monitor aeolian dune formation and dynamics on the upper-beach, high-resolution terrestrial laser scanning techniques from permanent instrument stations, recording data continuously, were used. In this way, morphological changes could be investigated at an appropriate temporal and spatial scale, allowing the characterization of ephemeral dune dynamics. In practice, the best temporal resolution for this purpose, given the instruments and conditions, was found to be six-hourly laser scans to understand the development of the protodunes with a height ranging from 0.15 to 0.42m formed under an along-shore wind above 7 m/s (Montreuil et al. 2020); see Figure 2.6. With the terrestrial laser scanning techniques (accuracy: 5mm), point clouds were acquired every hour (using the Riegl® VZ-2000, see Figure 2.5) in subsequent survey periods each lasting 36 hours. The resulting point clouds (comprising 95,500 points per survey) were used to generate digital elevation models (DEMs) for each point in time with a cell size of 0.25cm; see Figure 2.7. Based on this time series of DEMs, the differences between consecutive time periods could be visualized individually and in a cumulative way, resulting in the visualization of microscale morphological changes alongside aggregate outcomes of such processes. Please see Montreuil et al. (2020) for a more detailed account of this.

The example of monitoring of the protodunes of the Belgian coast (Figure 2.7) illustrates a number of characteristic features of how data acquisition, sampling, storage, and analysis processes in monitoring are currently being transformed through technological development. It shows how the presence of exceedingly vast amounts of data, collected continuously at high temporal and spatial resolutions, tend to inform research processes oriented more towards data mining and filtering and how such analysis processes may link understandings of the same processes across different temporal and spatial scales. In comparison, most data acquisition was extremely costly until very recently and therefore observations were typically limited to carefully selected samples of data for specific times and places. For example, aerial imagery was typically recorded at great cost and/or only at long intervals, depending on the location (Christensen 2013). Additionally, for such imagery to be useful to monitoring, it must be interpreted and classified, which is a delicate and painstaking process when conducted manually.

Figure 2.5 (Left) Riegl® VZ-2000 permanent laser scanner, overlooking the beach (to the right).

Source: Monbaliu et al. (2020).

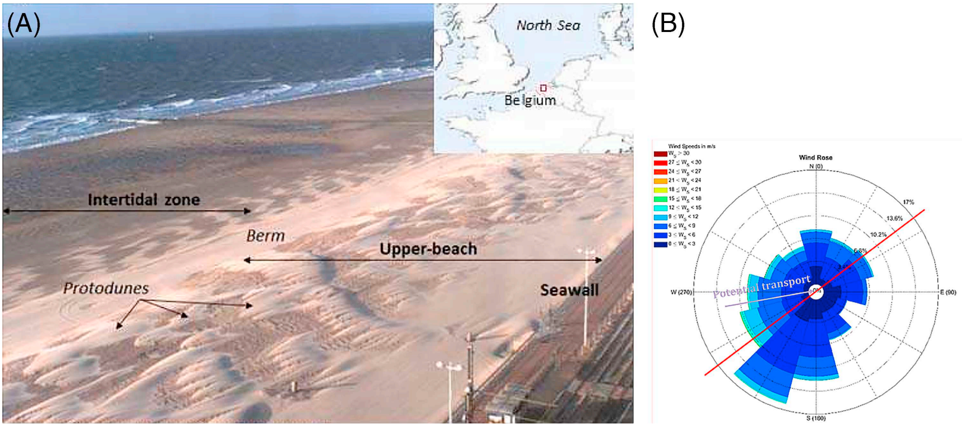

Figure 2.6 (A) A photograph with the presence of fully developed protodunes at the Mariakerke site of the project on April 26 at 18.00. The wind is blowing from the bottom left in the photo. (B) A figure showing the annual wind directions in Ostend, Belgium.

Source: After Montreuil et al. (2020).

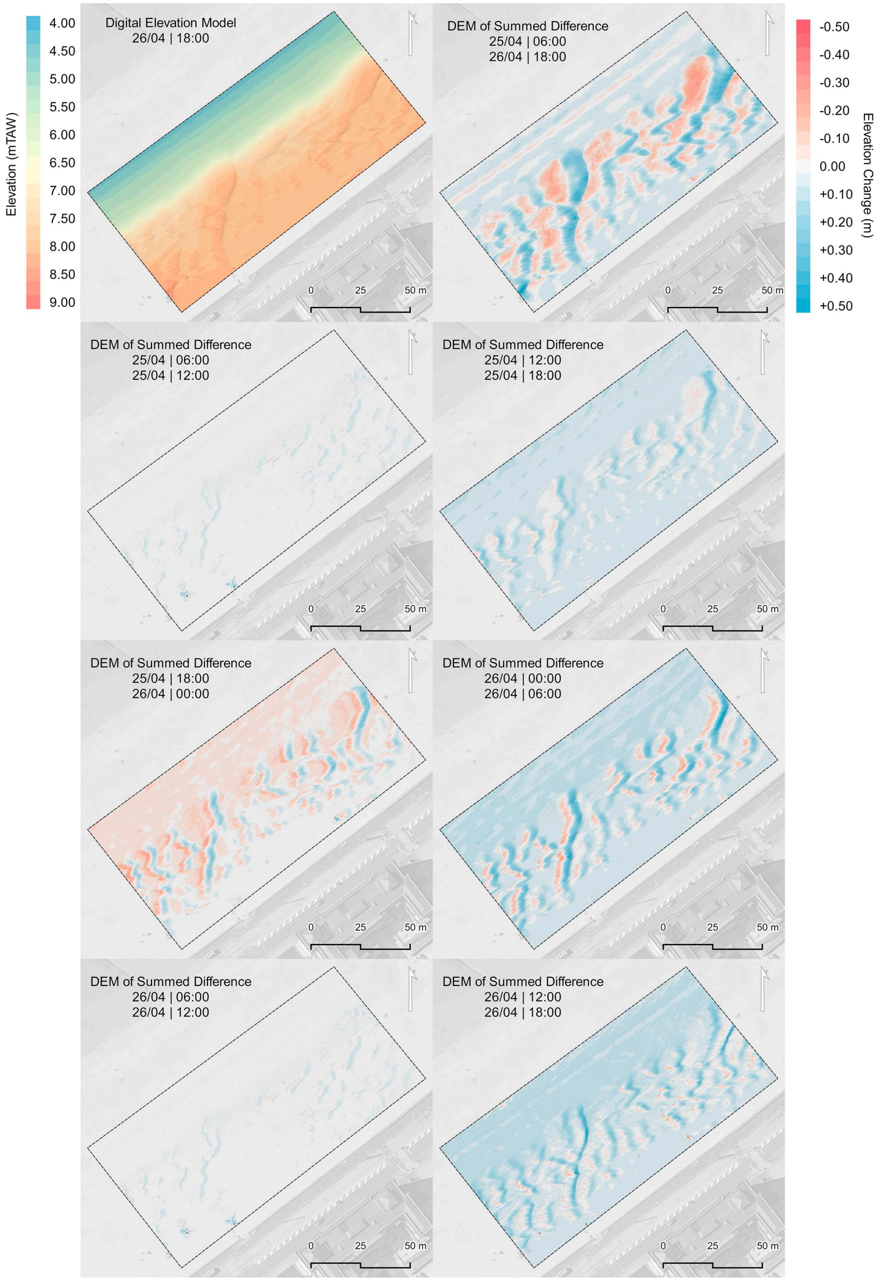

Figure 2.7 Digital elevation model (DEM) of the fully developed protodunes on April 26, 2018, at 18.00 and (top right) and DEM of differences (DoDs) showing the differences between the formation on April 25 at 6.00 and the fully developed protodunes on April 27 at 18.00 (top left). Below are six DoDs, showing summed elevation differences between consecutive surveys with a temporal resolution of observations of six hours.

Credit: Data, analysis, and cartography: Lars De Sloover, Department of Geography, Ghent University, Belgium, 2022.

This meant that until recently, only a limited area of land could be covered, and only at certain time intervals (Christensen et al. 2017). Similar limitations applied, and indeed still apply, to in situ fieldwork observations and most of the wide range of other methods used in monitoring. Therefore, sampling has traditionally been performed before acquisition and analysis of data, which then in turn has focused on deriving generally applicable insights about habitat change and persistence from relatively few observations. In contrast, current observation platforms tend to supply vast datasets that create an increasing demand for research processes where data are sampled after acquisition and where analysis to an increasing extent is unrestricted by limits imposed by temporal resolution. This is the case, for example, with respect to imagery collected as part of the Sentinel programme of the European Environment Agency (EEA), where researchers are able to develop land cover and habitat classifications directly from archives of continuously recorded imagery in combination with other types of data (Zanaga et al. 2021). Such imagery is recorded on a continuous basis at high temporal resolutions, in the same way that observations were made on the Belgian coast described above. This creates a situation where analysis efforts in monitoring tend to shift from being focused on design of observational processes to being focused on data mining, sorting, filtering, selection, and aggregation of already existing data; see example in chapter 9. In combination with deep learning algorithms and other forms of artificial intelligence used to classify data, this advent of big data processing techniques has tended to create situations of data excess, where too much data is available for it to be taken into account. This has had a range of different effects on monitoring. As such, the field is currently being transformed from a situation where research questions were formulated with respect to highly focused, specialized arrays of observation and analysis procedures to a situation where hypotheses may be tested with reference to large existing collections of observations. In this way, monitoring is becoming an increasingly flexible, explorative field of research, testing the limits of how observation may be transformed into knowledge.

Key messages

- In this chapter, we have briefly discussed some of the most important issues taken up in this book, starting with common types of monitoring and what they are for, including an understanding of who wants the results of monitoring and who could benefit from them.
- There are a large number of complementary ways to collect data, although in situ measurements are a constant factor because much of the detailed knowledge of biodiversity is hard to collect from remote sensors.
- Both imagery and data have become freely accessible in an unprecedented way, and researchers need to be flexible and incorporate both historical and current datasets potentially from different sources, making monitoring into a multidisciplinary field.
- The example of long-term national monitoring in the UK describes the issue of flexibility, with new and/or more data to incorporate into the scheme. The other example shows how the use of new technology in permanent networks of in situ devices, so common to monitoring in oceans, can be used to capture swift changes in other settings such as dune formations.

Study questions

1 What is the difference between the various types of monitoring, and to whom are they typically directed? Think about who else can benefit from the results and why.
2 How do the two types of data, quantitative and qualitative, differ, and what are they used for?
3 Read about the different types of data mentioned in this chapter, the ways of integrating them, and the amount of data needed to validate all steps. What are the main hindrances to data integration?
4 What can we learn from the near-constant changes in what is asked from monitoring, and what does that entail for the data provider who has to report the monitoring results?

Further reading

Much information on ongoing monitoring is only available on websites, and we recommend a search on sites, focusing on the type of monitoring of interest, because much can be learned from the success (as well as failures) of others.

Cavender-Bares et al. (2022) provide a recent review of monitoring biodiversity in relation to ways of collecting data and where different methods are helpful.

Lindenmayer and Likens (2018) provide a comprehensive read on ecological monitoring with common reasons for failure.

References

Amato, M.T. and Giménez, D. (2022) Quantifying root turnover in grasslands from biomass dynamics: application of the growth-maintenance respiration paradigm and re-analysis of historical data, *Ecological Modelling* 467, 109940. 10.1016/j.ecolmodel.2022.109940

Barr, C.J. and Wood, C.M. (2011) *The Sampling Strategy for Countryside Survey (Up to 2007)*, http://nora.nerc.ac.uk/19487

Brlík, V., Šilarová, E., Škorpilová, J., Alonso, H., Anton, M., Aunins, A., Benkö, Z., Biver, G., Busch, M., Chodkiewicz, T., et al. (2021) Long-term and large-scale multispecies dataset tracking population changes of common European breeding birds, *Scientific Data* 8, 21.

Bunce, R.G.H., Barr, C.J., Clarke, R.T., Howard, D.C. and Lane, A.M.J. (1996) Land classification for strategic ecological survey, *Journal of Environmental Management* 47, 37–60. doi: 10.1006/jema.1996.0034

Bunce, R.G.H., Barr, C.J., Clarke, R.T., Howard, D.C. and Scott, W.A. (2007) *ITE Land Classification of Great Britain 2007*. NERC Environmental Information Data Centre. 10.5285/5f0605e4-aa2a-48ab-b47c-bf5510823e8f

Cavender-Bares, J., Schneider, F.D., Santos, M.J., Armstrong, A., Carnaval, A., Dahlin, K.M., Fatoyinbo, L., Hurtt, G.C., Schimel, D., Townsend, P.A., et al. (2022) Integrating remote sensing with ecology and evolution to advance biodiversity conservation, *Nature Ecology & Evolution* 6(5), 506–519. 10.1038/s41559-022-01702-5

Christensen, A.A. (2013) Mastering the land: mapping and metrologies in Aotearoa New Zealand, in Pawson, E. and Brooking, T. (eds) *Making a New Land*. University of Otago Press, pp. 310–327.

Christensen, A.A., Brandt, J. and Svenningsen, S.R. (2017) Landscape ecology, in Richardson, D., Castree, N., Goodchild, M.F., et al. (eds) *International Encyclopedia of Geography: People, the Earth, Environment and Technology*. Oxford, UK: John Wiley & Sons, pp. 1–10.

Congalton, R.G., Gu, J., Yadav, K., Thenkabail, P. and Ozdogan, M. (2014) Global land cover mapping: a review and uncertainty analysis, *Remote Sensing* 6, 12070–12093. doi: 10.3390/rs61212070

Environment Agency. (2003) *River Habitat Survey Manual*. Bristol, UK: Environment Agency.

Eriksson, L., Nordlund, A., Olsson, O. and Westin, K. (2012) Recreation in different forest settings: a scene preference study, *Forests* 3, 923–943. doi: 10.3390/f3040923

European Commission. (1992) Council Directive 92/43/EEC of 21 May 1992, https://ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.htm (Accessed November 1, 2022).

European Commission. (2022) Monitoring and evaluation, https://ec.europa.eu/neighbourhood-enlargement/monitoring-and-evaluation_en (Accessed June 3, 2022).

European Environment Agency. (1999) Monitoring definition, https://www.eea.europa.eu/help/glossary/eea-glossary/monitoring (Accessed June 3, 2022).

Filazolla, A. and Cahill, F.J. (2021) Replication in field ecology: identifying challenges and proposing solutions, *Methods in Ecology and Evolution* 12, 1780–1792.

Fischer, M., Bossdorf, O., Gockel, S., Hänsel, F., Hemp, A., Hessenmöller, D., Korte, G., Nieschulze, J., Pfeiffer, S., Prati, D., et al. (2010) Implementing large-scale and long-term functional biodiversity research: the Biodiversity Exploratories, *Basic and Applied Ecology* 11(6), 473–485. 10.1016/j.baae.2010.07.009

Flanders Marine Institute (VLIZ). (2022) Climate Resilient Coast Project, CREST, http://www.crestproject.be/nl (Accessed June 3, 2022).

HELCOM Baltic Marine Environment Protection Commission. (2022), Home page, https://helcom.fi/ (Accessed June 3, 2022).

Henrys, P.A. and Jarvis, S.G. (2019) Integration of ground survey and remote sensing derived data: producing robust indicators of habitat extent and condition, *Ecology and Evolution* 9(14), 8104–8112. 10.1002/ece3.5376

Henrys, P.A., Smart, S.M., Rowe, E.C., Jarvis, S.G., Fang, Z., Evans, C.D., Emmett, B.A. and Butler, A. (2015) Niche models for British plants and lichens obtained using an ensemble approach, *New Journal of Botany* 5(2), 89–100. 10.1179/2042349715Y.0000000010

Holmes, N.T.H., Newman, J.R., Chadd, S., Rouen, K.J., Saint, L. and Dawson, F.H. (1999) *Mean Trophic Rank: A User's Manual*. Bristol, UK: Environment Agency.

Houk, P. and van Woesik, R. (2013) Progress and perspectives on question-driven coral-reef monitoring, *BioScience* 63(4), 297–303. 10.1525/bio.2013.63.4.10

Hurlbert, S.H. (1984) Pseudoreplication and the design of ecological field experiments, *Ecological Monographs* 54(2), 187–211.

Jackson, D. (2000) *Guidance on the Interpretation of the Biodiversity Broad Habitat Classification (Terrestrial and Freshwater Types): Definitions and the Relationship with Other Habitat Classifications*. JNCC Report, No. 307, Peterborough, UK.

Jeong, S., Jonghan Ko, J. and Yeom, J.-M. (2022) Incorporation of machine learning and deep neural network approaches into a remote sensing–integrated crop model for the simulation of rice growth, *Scientific Reports* 12, 9030. 10.1038/s41598-022-13232-y

Joint Nature Conservation Committee. (2022) National vegetation classification, https://jncc.gov.uk/our-work/nvc/ (Accessed June 3, 2022).

Khair, N.K.M., Lee, K.E. and Mokhtar, M. (2021) Community-based monitoring for environmental sustainability: a review of characteristics and the synthesis of criteria, *Journal of Environmental Management* 289, 112491. doi: 10.1016/j.jenvman.2021.112491

Lindenmayer, D. and Likens, G.E. (2018) *Effective Ecological Monitoring*. Clayton South, Australia: CSIRO Publishing.

Macgregor, C.J., Thomas, C.D., Roy, D.B., Beaumont, M.A., Bell, J.R., Brereton, T., Bridle, J.R., Dytham, C., Fox, R., Gotthard, K., et al. (2019) Climate-induced phenology shifts linked to range expansions in species with multiple reproductive cycles per year, *Nature Communications* 10, 4455.

Merchant, C.J., Minnett, P.J., Beggs, H., Corlett, G.K., Gentemann, C., Harris, A.R., Hoyer, J. and Maturi, E. (2019) Global sea surface temperature, in Hulley, G.C. and Ghent, D. (eds) *Taking the Temperature of the Earth*. Elsevier, pp. 5–55. 10.1016/B978-0-12-814458-9.00002-2

Minichiello, V., Aroni, R. and Hays, T. (2008) *In-Depth Interviewing. Principles, Techniques and Analysis*. 3rd edn. Australia: Pearson Australia Group.

Monbaliu, J., Mertens, T., Bolle, A., Verwaest, T., Rauwoens, P., Toorman, E., Troch, P. and Gruwez, V. (eds) (2020) *CREST Final Scientific Report: Take Home Messages & Project Results*. VLIZ Special Publication 85, Universiteit Gent, Belgium.

Montreuil, A.-L., Chen, M., Brand, E., De Wulf, A., De Sloover, L., Dan, S. and Verwaest, T. (2020) Early-stage aeolian dune development and dynamics on the upper-beach, *Journal of Coastal Research* (Special Issue) 95, 336–340. 10.2112/SI95-065.1

Morrison, C.A., Auniņš, A., Benkő, Z., Brotons, L., Chodkiewicz, T., Chylarecki, P., Escandell, V., Eskildsen, D., Gamero, A., Herrando, S., et al. (2021) Bird population declines and species turnover are changing the acoustic properties of spring soundscapes, *Nature Communications* 12, 6217.

Murray-Bligh, J. (1999) *Procedures for Collecting and Analysing Macro-invertebrate Samples*. Bristol, UK: Environment Agency.

National Oceanic and Atmospheric Administration. (2022) Satellites, https://www.noaa.gov/satellites (Accessed June 3, 2022).

Norton, L.R., Maskell, L.C., Smart, S.M., Dunbar, M.J., Emmett, B.A., Carey, P.D., Williams, P., Crowe, A., Chandler, K., Scott, W.A., et al. (2012) Measuring stock and change in the GB countryside for policy: key findings and developments from the Countryside Survey 2007 field survey, *Journal of Environmental Management* 113, 117–127. doi: 10.1016/j.jenvman.2012.07.030

OSPAR Commission 30th. (2022) Home page, https://www.ospar.org/ (Accessed June 2, 2022).

Priyadarshi, A., Chandra, R., Kishi, M.J., Smith, S.L. and Yamazaki, H. (2022) Understanding plankton ecosystem dynamics under realistic micro-scale variability requires modeling at least three trophic levels, *Ecological Modelling* 467, 109936. 10.1016/j.ecolmodel.2022.109936

Programme of the European Union. (2022) Copernicus Europe's eyes on Earth, Copernicus Services, https://www.copernicus.eu/en/copernicus-services (Accessed June 3, 2022).

Rodwell, J.S. (2006) *NVC Users' Handbook*. Peterborough, UK: Joint Nature Conservation Committee. All volumes are available at: https://jncc.gov.uk/our-work/nvc/

Sastri, A.R., Christian, J.R., Achterberg, E.P., Atamanchuk, D., Buck, J.J.H., Bresnahan, P., Duke, P.J., Evans, W., Gonski, S.F., Johnson, B., et al. (2019) Perspectives on in situ sensors for ocean acidification research, *Frontiers in Marine Science* 6, 653. https://www.frontiersin.org/article/10.3389/fmars.2019.00653

Smart, S.M., Jarvis, S.G., Mizunuma, T., Herrero-Jáuregui, C., Fang, Z., Butler, A., Alison, J., Wilson, M. and Marrs, R.H. (2019) Assessment of a large number of empirical plant species niche models by elicitation of knowledge from two national experts, *Ecology and Evolution* 9(22), 12858–12868. 10.1002/ece3.5766

Sparks, T., Garforth, J. and Whittle, L. (2020) A comparison of Nature's Calendar with Gilbert White's phenology, *British Wildlife* April, 271–275.

Sparrow, B.D., Edwards, W., Munroe, S.E.M., Wardle, G.M., Guerin, G.R., Bastin, J.-F., Morris, B., Christensen, R., Phinn, S. and Lowe, A.J. (2020) Effective ecosystem monitoring requires a multi-scaled approach, *Biological Reviews* 95(6), 1706–1719. 10.1111/brv.12636

Stevens, J.P., Blackstock, T.H., Howe, E.A. and Stevens, D.P. (2004) Repeatability of Phase 1 habitat survey, *Journal of Environmental Management* 73(1), 53–59.

Stewart-Oaten, A. (1996) Problems in the analysis of environmental monitoring data, in Schmitt, R.J. and Osenberg, C.W. (eds) *Detecting Ecological Impacts: Concepts and Applications in Coastal Habitats*. San Diego, CA: Academic Press, pp. 109–131.

Sundli Tveit, M., Ode Sang, Å. and Hägerhäll, C.M. (2013) Scenic beauty: visual landscape assessment and human landscape perception, in Steg, L., van den Berg, A.E. and de Groot, J.I.M. (eds) *Environmental Psychology: An Introduction*. 1st edn. Chichester, UK: BPS Blackwell.

Ten, A., Kaushik, P., Oudeyer, P.Y. and Gottlieb, J. (2021) Humans monitor learning progress in curiosity-driven exploration, *Nature Communications* 12, 5972. 10.1038/s41467-021-26196-w

UKCEH Countryside Survey. (2021) Land cover maps, https://www.ceh.ac.uk/ukceh-land-cover-maps (Accessed June 3, 2022).

UKCEH Countryside Survey. (2022) Home page, https://countrysidesurvey.org.uk/ (Accessed June 3, 2022).

UKCEH, Environmental Information Data Centre. (2022) ITE land classification of Great Britain (1990–2007), https://catalogue.ceh.ac.uk/documents/b86b3572-f480-48e1-9d31-5d3880b7f213 (Accessed May 15, 2022).

Underwood, A.J. (1992) Beyond BACI: the detection of environmental impacts on populations in the real, but variable, world, *Journal of Experimental Marine Biology and Ecology* 161, 145–178.

United Nations, Economic Commission for Europe. (2016) *Environmental Monitoring and Assessment – Guidelines for Developing National Strategies to Use Biodiversity Monitoring as an Environmental Policy Tool for Countries of Eastern Europe, the Caucasus and Central Asia, as well as Interested South-Eastern European Countries*, United Nations Publications, ECE/CEP/176. https://unece.org/sites/default/files/2020-12/1528741_E_inside.pdf

U.S. Geological Survey. (2022) The Landsat satellite missions, https://www.usgs.gov/landsat-missions/landsat-satellite-missions (Accessed May 14, 2022).

van Swaay, C.A.M., Dennis, E.B., Schmucki, R., Sevilleja, C., Balalaikins, M., Botham, M., Bourn, N., Brereton, T., Cancela, J.P., Carlisle, B., et al. (2019) *The EU Butterfly Indicator for Grassland Species: 1990–2017*. Technical Report. Butterfly Conservation Europe.

Wang, F., Zhu, J., Chen, L., Zuo, Y., Hu, X. and Yang, Y. (2020) Autonomous and in situ ocean environmental monitoring on optofluidic platform, *Micromachines* 11, 69. 10.3390/mi11010069

Wilson, N.J., Mutter, E., Inkster, J. and Satterfield, T. (2018) Community-based monitoring as the practice of Indigenous governance: a case study of Indigenous-led water quality monitoring in the Yukon River Basin, *Journal of Environmental Management* 210, 290–298.

Wood, C.M., Bunce, R.G.H., Norton, L.R., Maskell, L.C., Smart, S.M., Scott, W.A., Henrys, P.A., Howard, D.C., Wright, S.M., Brown, M.J., et al. (2018) Ecological landscape elements: long-term monitoring in Great Britain, the Countryside Survey 1978–2007 and beyond, *Earth System Science Data* 10, 745–763. 10.5194/essd-10-745-2018

Zanaga, D., Van De Kerchove, R., De Keersmaecker, W., Souverijns, N., Brockmann, C., Quast, R., Wevers, J., Grosu, A., Paccini, A., Vergnaud, S., et al. (2021) ESA WorldCover 10 m 2020 v100. 10.5281/zenodo.5571936