„Biodiversity monitoring & indicators“
White paper of the Commission for Biodiversity Research to the Senate of the DFG (*SKBDF*)

Preamble

Biodiversity on Earth is in crisis: ever increasing pressures of a growing human population with concomitantly growing demands for nutrition, energy and physical space constrain the prospectus of many populations and communities of organisms to persist in the long run. This also places the functions these organisms carry in the biosphere at risk. The working group *"Biodiversity monitoring & indicators"* of the DFG Senate's Commission for Biodiversity Research *[SKBDF]* has taken up this thread to identify significant gaps, develop priorities and suggest recommendations, mostly from the perspective of basic research. We explicitly acknowledge that for many topics of high relevance in applied sciences, recommendations, methodologies and regulations with an emphasis of local to national practicalities already exist with regard to the monitoring of biodiversity change.

In the national biodiversity strategy for Germany, for example, numerous indicators for the monitoring of biodiversity and ecosystem functions have been defined. These indicators allow to measure the actual status of the environment and to relate this status to benchmarks which more or less reflect the situation about 1-3 decades ago. Derivation and definition of indicators was only possible because, in Germany, a dense (though incomplete) documentation of species and habitats exists. Most of this knowledge had NOT been generated with monitoring purposes in mind. Still, this knowledge now provides the most valuable grounds for conservation of biodiversity and strategic development. As a consequence, many measures are now being suggested as part of the mandatory implementation of the national biodiversity strategy, and indicators are being used to assess as to how far goals and benchmarks have been reached.

In contrast to such a monitoring system that is basically driven by the wish to 'restore' putatively 'healthy' environmental 'equilibrium' conditions through guided application of best practice models, an indicator-based monitoring in basic ecological research does not aim at reaching any particular benchmark conditions. Rather, the goal here is to validly assess the present status of biodiversity and ecosystem functions. Usually, in the absence of long-term baseline data on the biodiversity of the systems in question, functionality and resilience of ecosystems will be in the centre of research interests, supplemented (as far as possible) by biodiversity inventories. The critical question is whether under such conditions, especially if high biodiversity is prevalent (like in tropical regions) functionally motivated monitoring programs can be developed that may serve simultaneously to assess ecosystem health AND allow for inferences on biodiversity. Whether it is really possible to extrapolate from of any functionally centred monitoring to local or regional biodiversities, needs to be empirically established. If this should turn out to be the case (in tropical realms with poorly known biodiversity), this might reciprocally open up new directions for monitoring in areas with rather well established biodiversity data.

The aim of this present paper was not to review or reform existing monitoring procedures. Rather our goal is to identify areas where basic research is needed to improve, and possibly unify, sectoral scattered approaches to better fit requirements in a rapidly changing world, especially in the framework of the UN-CBD and its implementations. Under this latter perspective, the recommendations explicated below can be seen as suggestions how the general aim of sustainability that has inspired the UN-CBD can be translated into concrete research goals in the fields of basic science amenable to DFG-funding.

The challenge

Rapid anthropogenic change of most environmental conditions on Earth necessitates to comprehensively follow and document the effects of changes (such as in climate or land-use) on the structure and functionality of our biosphere. Such knowledge is essential for science-based projections, scenarios, and the subsequent informed choice between management options. Globally agreed standards and methods do exist for the monitoring of abiotic environmental dimensions (such as climate; or chemistry and physics of soil, water and atmosphere). In contrast, monitoring of the living world is far more complex. Only sectoral approaches are thus far established (i.e. monitoring systems and schemes for particular biota or organisms), but establishing comprehensive guidelines for biotic monitoring has hardly been achieved. The major challenge here is the extreme extent of biodiversity. Given that the species of organisms that thrive on Earth are still very incompletely known even in terms of basic taxonomy, it is obvious that more advanced deductions can at best be obtained for a small number of groups of organisms, notably for the better explored (but less diverse) regions of the northern hemisphere. For example, sound knowledge of species distributions or abundances is sparse apart from a few selected (and more obvious) taxa. Even less is known as to how these distributions and abundances change under human influences. Finally, such type of biotic data is particularly incomplete for species-rich tropical realms.

Large-scale continental or even global patterns of spatial distributions are amenable to more sophisticated and rigorous analyses and modelling only for vascular plants, birds, or (in part) butterflies. For practically all other groups of organisms (especially non-vascular plants, most invertebrates, fungi and microbes, but even for many vertebrates such as the majority of fish or amphibians) biodiversity has been insufficiently surveyed and mapped in most regions. Even if the species are taxonomically described, knowledge about their spatial distribution and abundance is often far too scant to allow for meaningful assessments of their population trends or range shifts.

A major obstacle here is the lack of taxonomic expertise worldwide, termed ***taxonomic impediment***. This implies that even if relevant biotic samples were being taken in coordinated (national or international) monitoring programs with appropriate spatial and temporal replication, far too few scientists are available who were able to provide identifications of all these organisms in the required quality and precision. In particular, (near) complete assessments of local biodiversity (so-called ***all taxa inventories***) would be so demanding that they could at best be achieved at a very small number of localities, and certainly not in dense temporal replication.

Since more than 20 years, therefore, ecologists have aimed at identifying ***biodiversity indicators***, i.e. individual species or selected groups of organisms whose diversity patterns can serve as surrogates for “overall” biodiversity and its change in space and time. The consensus now is that despite all research efforts “universal” biodiversity indicators do not exist, and in all likelihood cannot be found. The diversity of responses of organisms to changes in their environment is almost as large as the diversity of living species. Accordingly, biodiversity patterns along environmental gradients are often idiosyncratic for each group of putative indicators. The extent of concordances in addition depends on the scale of observation, and may vary within the same set of “indicator organisms” from narrow to extensive environmental gradients. Certain organisms may work perfectly well as indicators in one region or context, but cannot be universally applied since they are too rare or entirely absent in other regions or ecosystems. Moreover, biodiversity can be partitioned into two main components (local richness or ***alpha-diversity***, and spatial or temporal turnover or ***beta-diversity***). A growing number of studies, however, show that these two components of biodiversity may behave completely differently through space and time, such that apparent good candidate groups for predicting alpha-diversity may completely fail with regard to species turnover, and vice versa.

This leads to the tentative conclusion that one single, manageable suite of universal indicator taxa for the purpose of biodiversity monitoring (in analogy to the well defined number of physical, chemical and geographical parameters in environmental monitoring) will not be found in the near future, and may from intrinsic regions never be agreed upon, except for particular subsets of regions or ecosystem types.

The diversity of possible goals of biodiversity monitoring – necessities to be more specific

The goals of and motivations for biodiversity monitoring vary substantially across stakeholders and regions. Accordingly it is necessary to specify these goals in advance, since selection of appropriate indicator systems and methodological approaches will depend on this context. If ***effects of climate change*** on biodiversity are the focus, monitoring should concentrate on organisms that occur at sensitive, and relatively well defined, borders between habitats (ecotones). A key example is the GLORIA initiative to monitor and analyse climate-driven changes in alpine and subnival vegetation of high mountain tops worldwide. Here, highly standardized methods of vegetation ecology are put in place which can be implemented independently of the floristic region an individual mountain area is situated in. The relative cover of all (vascular) plant species in small units of area is noted, and this procedure is repeated at intervals of 5-10 years (Gottfried et al. 2012). Given the moderate plant species richness of mountain tops all over the world, this type of monitoring is demanding, but still manageable. Basically a similar approach would be possible at upper tree lines in mountain regions, though the expenditure of resources would be far more demanding (higher species richness of plants, especially in tropical mountain regions; larger size of monitoring sites required, since also woody plants need to be covered). It is, however, quite unrealistic to adapt a similar approach with acceptable resource demand to really speciose ecosystems, for example to the rather weakly defined and continuous ecotones between forest zones in any tropical elevational gradient.

Another important application area for biodiversity monitoring is concerned with ***effects of land-use change***. In this field, universal solutions will not become available due to the manifold dimensions of ongoing land-use changes in different regions and ecosystems. Abandoning traditional land-use or reducing its intensity (as observed in many rural regions in Europe) requires different indication systems to be followed, as opposed to intensification of land-use or conversion of near-natural ecosystems for agriculture, forestry, or human settlements. For this field, however, a plethora of case studies has been performed in temperate as well as tropical climate zones, allowing for the identification of regionally or nationally tried and tested specific indicator systems (e.g. Gardner et al., 2008; Barlow et al., 2007; Kessler et al., 2011; Gardner, 2011).

Again another suite of motivation for the implementation of biodiversity monitoring programs is driven by ***nature conservation concerns***. This may include the (more or less systematic) surveying of populations of selected target organisms over a range of spatial scales, from regional across national to international. Frequently, the selection of target species to be monitored is based on regional or national "rarity", or on legal definitions and requirements (such as CITES, national conservation laws, or Annexes to the EU habitats directive), rather than on scientific arguments and evidence. There is an extensive literature on species monitoring programs relative to conservation efforts (see discussion and many references in *Trends in Ecology and Evolution* **26**: 107-109, 2011).

Monitoring of selected organisms across large spatial (and also across extended temporal) scales usually can only be implemented by massively integrating ***citizen scientists***. These volunteers deliver their observations to central repositories, today especially by using web-based technology. Highly successful examples include surveys of breeding birds (coordinated through *BirdLife International*) or the British *Butterfly Monitoring Scheme* (whose spin-offs now are running in many European countries). Besides these monitoring efforts (managed by NGOs) also many governmental bodies at various levels of responsibility collect biodiversity data (e.g. geo-referenced records of plant or animal observations). These data would be most valuable to be included in assessments of the *status quo* of current biodiversity as well as for projections of trends. The major challenge here is that such recording schemes are often not coordinated with regard to methodologies of observation, storage of data, and quality control of entries. Therefore, especially in federally organized states like Germany, the availability of biodiversity data as well as the access to them is often hindered by organisational difficulties and unresolved responsibility conflicts. This fragmentation is a serious obstacle in integrating available biodiversity data, often obtained through the investment of taxpayer's money, into more comprehensive frameworks.

Not only rare or endangered species are being monitored. There are also manifold monitoring programs to ***survey 'unwanted' organisms***, such as invasive alien species or pests of economical or medical importance. Most of these monitoring efforts are carried out by governmental authorities, and their degree of coordination and methodological standardization varies widely. As with conservation-oriented monitoring the selection of target organisms to be covered is often dominated by political and legal considerations rather than scientific evidence.

To sum up, the majority of existing biodiversity monitoring schemes do not address entire communities (like vegetation units, as in GLORIA). Far more frequently selected species or groups of organisms are monitored, but their relevance as indicators beyond the specific purpose for which they have been selected is often questionable. Transfer of information between monitoring schemes is complicated by methodological inconsistencies (with regard to data collection as well as data storage) and often also suffers from fragmentation due to political or organisational constraints.

What to monitor: individual species, assemblages, or processes?

In view of the multiplicity of approaches to monitor different aspects of biodiversity (see above), there is little scope that unified universal indicator systems can ever be developed, on which all responsible parties would be able and willing to agree. In this situation, the working group “Monitoring and Indicators” within the SKBDF has discussed possibilities to develop innovative approaches that go beyond the level of individual (and by necessity: specific) organisms. Such novel approaches would be particularly relevant for the integrated biodiversity projects that are currently running under DFG funding. Here, the overarching aspect of ***ecosystem function*** should gain stronger emphasis. Especially, it would be much desired to develop monitoring approaches and indicator systems that allow assessing the functional integrity of ecosystems by means of standardised ***quantitative parameters***. These measures could then be related to assessments of biodiversity.

A critical issue in this connection is the spatial and temporal scale of planned monitoring activities and the interdependency between the selection of indicator systems and the specific ecosystems and processes to be evaluated. With regard to ongoing DFG-funded activities one major question also is whether it is possible to derive common indicator systems for rather well-characterized (and less species rich) <u>temperate-zone</u> ecosystems in Central Europe (e.g. the *Biodiversity Exploratories*) as well as for less well-characterized, and far more species rich, <u>tropical</u> ecosystems (including *biodiversity hotspots*, e.g. in Ecuador, Indonesia, China). Along this line, two complementary approaches were discussed: ***organisms*** or ***interacting modules*** as monitoring targets.

1. Selected **organisms** (or groups thereof) as indicators

<u>Micro-organisms</u>: established methods in microbial ecology include metagenomics (analysis of 16S rRNA and other sequence markers, via high-throughput sequence analysis) and the assessment of specific metabolic pathways (via fluorescence in situ hybridisation, *FISH*), often in combination with isotopic markers. Metagenomics offers insight into the ‘total’

diversity of microbes at a site, whereas FISH establishes which fraction of microbial diversity is metabolically active. This distinction is important, under a functional perspective, since many microbial species are more or less ubiquitous, but only occur as dormant inactive spores at many sites and/or times.

All approaches in microbial ecology are highly demanding in terms of resources and working effort, and they are associated still with a substantial error rate (extraction of DNA or mRNA, PCR, cloning efficiency). Metagenomic analyses deliver enormous amounts of data that may define sites to a high degree of precision. Longer term experience with regard to the suitability and feasibility of these approaches for monitoring purposes, however, is still lacking. The SKBDF recommends that rigorous tests should be established, primarily starting with better known temperate-zone ecosystems (e.g. the *Exploratories*), to assess whether metagenomic or metabolomic procedures can be implemented for standardised functionality-oriented monitoring of microbial diversity in soil or water bodies with acceptable resource demand. A critical issue here is the enormous small-scale heterogeneity in these ecosystem compartments.

<u>Birds</u>: Surveys of bird assemblages are one of the most comprehensive sources of long-term monitoring data that are available today. Standardized universal recording methods exist, which can be globally implemented and deliver data of high comparability across regions and ecosystems. Birds hold many functions in ecosystems (as predators of animals and plants, seed dispersers, and as prey to higher-level consumers). They mostly act at rather large spatial scales (kilometres and above), hence integrating local habitat effects on a landscape scale. No other single group of animals is equally amenable to be used in monitoring efforts, since bird species richness is moderate, manageable and taxonomically well documented even in biodiversity hotspots. Bird monitoring can easily be implemented across large geographical and temporal scales. The integration of citizen scientists is well advanced, and allows for effective replication of monitoring beyond a scale that could be achieved with professionally trained ecologists. Hence, at least for terrestrial, limnetic and coastal ecosystems the inclusion of birds is recommended for all biodiversity monitoring efforts.

<u>Bats</u>: Bats are the most species-rich group of mammals. Like birds they comprise representatives of many different feeding guilds, and their flight activity renders them suitable to integrate local processes at the landscape scale (kilometres and above). Their lower species richness compared to birds (and also lower functional diversity in non-tropical ecosystems) can be seen as an advantage for simplifying monitoring, but also as a disadvantage in terms of lower ecological resolution. Bat monitoring strongly depends on acoustic recording. Automated methods need to be further improved to facilitate this process

of data accumulation. It is recommended to engage in developing and testing such automated acoustic recording methods for their usefulness in biodiversity monitoring, especially for forest ecosystems in tropical and temperate regions.

<u>Arthropods</u>: Arthropods are the most species rich group of animals on Earth, and their functional roles in ecosystems can hardly be over-estimated. Yet, it is especially their staggering species (and also their high functional) diversity that renders them impractical for universal biodiversity monitoring. Even within selected guilds or taxa (especially in tropical habitats) arthropod diversity is so high and taxonomic knowledge so incomplete that the scientific evaluation of relevant ecological samples is probably too demanding in terms of resources and required manpower. Experiences within the framework of the *Biodiversity Exploratories* exemplify this constraint. In addition, many arthropod species can only be surveyed during particular (often short-lived) life-cycle stages. Depending on the ecological and taxonomic group to be surveyed, collection methods differ widely. Hence, to be representative, either very massive multifaceted sampling programs would be required, or (more realistically) only very small subsets of arthropods (e.g. butterflies, dragonflies, or grasshoppers – all popular in conservation monitoring in the northern hemisphere) could be monitored. In most regions of the world, and especially in the tropics, knowledge of the *status quo* is so poor that this constrains any sound evaluation of possible changes to be observed. Therefore, the inclusion of (selected) arthropod groups in monitoring is recommended and feasible only if warranted by specific hypotheses to be tested, or if and where methodological and taxonomic problems do not pose serious obstacles.

<u>Vascular plants</u>: In terrestrial ecosystems these are the most important primary producers, they are responsible for habitat structures, and species identities are usually rather well known. Still, at least in tropical forest ecosystems total inventories can hardly be achieved (whereas this is a successful standard procedure in vegetation ecology of northern temperate biomes). In tropical forests, a focus on **trees** (instead of ‘total’ vascular plant diversity) seems feasible for standardised monitoring purposes. Due to their long life-cycles trees also provide additional advantages (for example, growth rings in their wood can be evaluated as monitors of recent climate history), so that even the tree individual may yield insight into the recent past of an ecosystem. Specific problems of trees as monitoring targets likewise arise from their longevity. For example, ecosystem changes may become visible with substantial delay, relative to more quickly responding short-lived organisms. Apart from collating mere species-abundance lists, monitoring of trees should comprise parameters such as growth rates, biomass, demography at population/plot level, leaf area index, and foliar nutrient contents, at least for the more common tree species of a stand. These more process-oriented parameters should be collected for early as well as late successional tree

species. If a selection of tree species for a monitoring program is necessary (for example due to resource constraints), the selection of target species should encompass functional and life-history traits to be as representative as possible.

Also **lianas** are ideal candidates for monitoring purposes (in tropical forest ecosystems). Many of them are pioneer plants and indicators of disturbances. Their species richness is modest and manageable. Most importantly, there is growing evidence that lianas respond particularly strongly to habitat alterations in the course of climate and land-use change in the tropics. In addition, **neophytic** (i.e. anthropogenically introduced) **plants** could be highly suitable indicators and should be monitored. Neophytes have the potential to become invasive, and then not only indicate environmental changes, but are an essential part of such ongoing changes. Herbaceous and epiphytic plants, in contrast, are much less suitable for inclusion in universal monitoring schemes (at least in species-rich tropical biomes) because of taxonomic as well as methodological problems associated with their standardised recording.

Biological crusts (lichens and mosses): in northern temperate zones these organisms have a long and successful history as environmental indicators in relation to atmospheric pollution and aerosol depositions. Standard methods for surveying them are well established. The SKBDF recommends to systematically explore at selected sites in the tropics, whether this bioindication potential can be transferred to tropical lichens and biological crusts. For that goal, the taxonomic characterization of these organisms as well as their environmental relationships needs to be established to a degree that allows for standard use in field surveys.

The above considerations exemplify that it is still controversial which organisms to include for what specific purposes in any biodiversity-oriented monitoring scheme. These problems are particularly severe in tropical ecosystems. The SKBDF therefore recommends to implement a specific research project targeted at the large amount of biodiversity data that have been, and continue to be, collected in the coordinated DFG projects (such as Research Units, Focal Programs, and SFBs) in temperate as well as tropical regions. These large data treasures should be systematically mined, with appropriate up-to-date statistical and modelling tools, to extract organisms (or groups of organisms) that appear to be particularly responsive to climate and land-use changes, respectively. Once such candidate groups have been extracted, their suitability and indication potential should be validated against new field data. In addition to specialists in data mining and modelling, experts in the ecology and taxonomy of the respective plant and animal groups should be incorporated into this exercise.

The goal would be to identify suites of organisms that show clear and robust responses to environmental change, but at the same time are feasible candidates to put monitoring into practice. Ideally, such indicator systems would comprise organisms that have high significance for ecosystem functioning and/or are deeply involved into biotic networks. The data from the highly replicated systematic surveys in the *Biodiversity Exploratories*, in particular, should provide unique material for this purpose, since here many different taxa and functional groups of organisms are included.

One commonality of DFG-funded coordinated research programs in biodiversity is that they all address ecological ***gradients***, however at very different spatio-temporal scales. Conducting meaningful meta-analyses on these data will be a challenge, especially for the study regions in tropical hotspot areas. To achieve comparability, a shift from species-centred to more functionally motivated analyses will probably be required.

The use of existing biodiversity data from ongoing coordinated research units under DFG-funding, in a kind of data-mining exercise, to search for components of biodiversity that are particularly sensitive to environmental change, or which otherwise share characters useful for monitoring, would be a prime example of data-driven research. In recent years, learning from data has developed as an important concept in scientific progress besides hypothesis-driven experimentation or surveys. The dual utilization of biodiversity data might thus allow for a promising mutual benefit between these two ways to do basic science – which otherwise often progress in segregation from another.

2. **Ecosystem processes and modules of interacting organisms** as indicators.

Classical monitoring has a focus on recording the presence or abundance of particular species or species groups. To complement these approaches, we here suggest developing novel experimental indication systems that rather yield information on certain ecosystem processes or the integrity of biotic interaction systems. Hence, instead of monitoring species or assemblages as “individuals”, the functional module becomes the prime target. This parallels the paradigmatic shift to be observed in present-day biodiversity research from ‘mere’ *species diversity* to *interactive* or *functional diversity*. As a pre-requisite, then, only systems lend themselves to implementation whose interacting components and functionalities are rather well characterized. Simple model systems that can be easily replicated and set out in different ecosystems could then be used to quantitatively assess, in rather short periods of time, the status of a particular ecosystem process in a given habitat.

One major challenge in that regard is the reliable quantification of interactions between species, and ‘ecosystem services’ provided by species or interactive modules. For example, flower visits through animals at a given plant species are not per se equivalent to pollination services. For monitoring purposes, the interactions and processes to be observed should also respond sensitively to environmental change. Ecosystem functions that may crucially depend on biodiversity include pollination success or seed removal rates. These could be quantified by placing standard model plants, or offering standard seed assemblages, in a sufficient number of replicates and assess how efficiently these two important ecosystem services are provided in the habitats under consideration. This approach, however, requires that in the surveyed ecosystem the respective plant-animal interactions are really decisive for pollination or the fate of seed. If such standardized data on ecosystem functions could then be related to standardized data on the system’s biodiversity (e.g. flowering plants, flower visitors, seed predators), this would allow for highly comparable data about relationships between biodiversity and ecosystem function, also in real-world ecosystems that have not been artificially assembled to assess such relationships in an experimental way. Vice versa, such measurements would also allow, in habitats of largely unknown biodiversity, to obtain evidence whether limitations to the respective ecosystem services must be expected that would point to low biodiversity.

In analogy, plant-herbivore interactions could be studied using simple community modules as probes. In more general terms, simple experimental community modules could provide ideal and more tractable units to measure biodiversity and its relationship to ecosystem processes than entire complex systems. This would be most helpful in assessing the relationship between species and functional diversity, or the degree of functional redundancy. The SKBDF therefore suggests that research projects should be started to develop, test and improve the use of small modules and experimental units to establish the role of biodiversity for important plant-animal interactions such as pollination, seed dispersal, seed predation, and herbivory.

As one example, so-called phytometers (i.e. potted plants of standardized size, quality and age) should be explored for their potential to serve as experimental community modules to measure the integrity of biological interactions across trophic levels such as herbivory or pollination. Once an informed selection of suitable plants has been achieved (e.g. herbs or small shrubs, probably with different focal plants depending on the climate and ecosystem context to be addressed?), phytometers could be placed in standardized manner in almost every terrestrial ecosystem. Important research questions to be tackled in the pilot phase are concerned with an appropriate selection of plants, and how to relate measurable traits at the phytometer scale to local biodiversity. Other critical issues to be solved are concerned with the problem that measurable effects will very often be conveyed through common and ecologically dominant organisms (e.g. main pollinators or defoliators), whereas important functions of biodiversity (such as insurance effects, responses to extreme conditions, non-linear relationships between biodiversity and ecosystem function) may not be easily detectable.

Litter bags of common size, filled with standardized leaf mixtures and exposed for one year in terrestrial systems, would provide a meaningful instrument for monitoring the functionality of another important ecosystem process (viz. decomposition of dead biomass). Again, the challenge will be to relate observable patterns in decomposition rates to biodiversities of the relevant organisms.

Once implemented, however, such simple biotic monitoring modules would allow for elegant meta-analyses across environmental gradients on all continents.

3. **Technical innovations** for the simplification of biodiversity monitoring.

Even for rather simple ecosystems, it is obviously (with current technology) impossible to assess biodiversity in its entirety. Especially the taxonomic impediment needs to be considered here again. While statistical methods have been advanced far to deal with incompleteness of real samples due to stochastic sampling effects, the only potential mode of teasing apart numbers of (often unknown) species in the absence of taxonomic knowledge is the use of molecular techniques (such as ***DNA barcoding***). It has not been established whether this approach will be successful with ‘all’ multicellular organisms, with their dramatic differences in biomass and abundance, at the level of entire natural communities (in analogy to microbial metagenomics, which also has to deal with critical methodological constraints, see above). Evidently, this field of research urgently needs to be further developed. Methods of community-wide analyses of sequence data for entire plant, fungal or animal communities could, at least in theory, become important tools in rapid biodiversity assessment and monitoring.

Technical innovation will also be required to develop the measurement of biotic interactions using community modules into a feasible standard method. For example, automatic video-recording of flower visits, in combination with automated identification of visitors using image-analysis software, would be a requirement to transfer such approaches from man-power intensive case studies to their application in standard monitoring.

In this regard, automated modes of acoustic monitoring have already progressed further (e.g. for ultrasonic bat calls in Europe and increasingly also in tropical areas), but still not to a degree that would allow reliable recognition of individual bat species only by means of appropriate software applications. Acoustic biodiversity monitoring offers particularly valuable opportunities, since it is a non-invasive approach, allows for simultaneous registration of calls of a variety of animals that employ acoustic communication (birds, bats, other mammals, amphibians, and many insects like grasshoppers, crickets, or cicadas), covers a relatively large spatial scale, and could yield a rich set of data on their presence, activity density, and differential activity periods.

Thus the further development of software tools to facilitate automated evaluation of acoustic long-term records would allow a leap forward in assessing functionally important fractions of animal biodiversity, without the need to sample individual specimens or to deploy scientists as observers for long periods of time in the study habitats. The major pre-requisite would be to assemble complete acoustic reference libraries for each ecosystems in question. The SKBDF therefore recommends intensifying research in that regard, especially in order to minimize error rates of existing systems and testing their validity also under more demanding tropical conditions (i.e. where species richness is far higher).

Very similar opportunities nowadays come into reach with regard to automated image analyses. At least for those (mostly larger sized) organisms that can be safely identified from images, progress in information makes it likely that within few years automated identification of voucher images taken by automatic camera traps or during field surveys can be achieved. The SKBDF suggests that pilot studies should be conducted in the framework of DFG-funded groups to develop working examples and test the versatility under field conditions. If successful, such technologies could speed up the processes that are currently most time-consuming in surveys of any organisms, namely processing and identifying samples. For monitoring purposes, however, such developments will mostly be relevant in those groups of organisms and those ecosystems where cryptic diversity is not a major issue.

While the above examples of technical innovation relate to improvements of the recognition of components of biodiversity at selected monitoring sites, another suite of ongoing technological developments will have strong positive effects on the spatial dimension of any monitoring exercises, viz. the upscaling from local (plot-scale) measurements to relevant landscape (and larger) scales. Spatially explicit monitoring on different spatial scales is hardly possible with only relying on plot based field surveys. Remotely sensed data and methods of digital image processing have been proven to support monitoring tasks successfully, by deriving structural, compositional and functional indicators. Monitoring requires operationally available satellite data with regular temporal repetition and constant data quality. To date, this data is delivered by passive multi- and hyperspectral instruments and active sensors as Radar (Radio Detection and Ranging) and LiDAR (Light Detection and Ranging). The current spatial resolution of operational data ranges from 30 m for applications on the landscape scale to 1 km and beyond for applications up to the global scale. High resolution data (<5 m to cm) are hitherto limited, partly only available from costly and mostly non-recurring (and thus, not operational) flight campaigns, but are particularly important for upscaling purposes from the plot to the landscape scale.

To derive meaningful indicators, passively or actively retrieved radiances have to be converted to biodiversity-related indicators. While the active systems primarily allow to retrieve information on the structure of ecosystems (such delivering structural indicators and derivatives), multi-/hyperspectral data additionally provide information on ecosystem traits and thus, information related to ecosystem functioning. Compositional indicators can be directly derived by species detection (e.g. hyperspectral tree species detection; Clark et al. 2005) or indirectly. An indirect method would e.g. derive structural habitat indicators from active instruments (as e.g. 3D-forest structure, canopy density etc.; Turner et al. 2005) which are then related to compositional indicators (e.g. bird diversity; Bradbury et al. 2005) by statistically derived transfer functions. Manifold information related to functional indicators can be retrieved from satellite data as e.g. plant phenological development (related to pollination and seed dispersal), stress in water relations (indicating changes in biological water cycle), productivity (indicating changes in carbon sequestration), LAI as an indicator of environmental stress (herbivory) or chemical leaf components indicating changes in the biogeochemical nutrient cycle (Chamber et al. 2007; Kokaly et al. 2009). Information on changes in canopy biochemistry can be also used as an indicator for vulnerability against herbivory (Izaguirre et al. 2006). The capabilities to derive spatially explicit indicators will become significantly boosted in near future with the launch of new space sensors as EnMAP (Environmental Mapping and Analysis Program; ESA's hyperspectral mission scheduled for 2015) or Tandem-L (DLR's Tandem Radar Mission).

The SKBDF recommends that these novel technological developments are actively tested for their potential to relate measurable attributes of ecosystems to their biodiversities. For those technical improvements that directly address the identification of biotic components of ecosystems, these relationships are immediately obvious. For many of the data that can be retrieved through remote sensing methodology, relationships to local biodiversities need always to be specifically established first (and re-validated again regularly by groundtruthing), but wherever feasible remotely sensed data will allow for much higher levels of spatial and temporal replication of assessments as would ever be possible by relying on organismal surveys alone.

Biodiversity monitoring: soil vs. above-ground systems

Of course, the functionality of terrestrial ecosystems must address above-ground as well as below-ground biota and processes. Functionality of soil compartments depends critically on soil animals, fungi, and protist as well as microbe populations. Soil faunas can be surveyed with well established standard extraction methods, but for many monitoring purposes these will in all likelihood not be feasible (see remarks under arthropods, above). Microbial and fungal communities are only amenable to analysis by molecular methods (metagenomics and allies). Metagenomics allows for identifying sequence diversities (see above) which can serve as a surrogate for species diversities. Since DNA extraction from soils is still technically demanding and usually incomplete (e.g. DNA of certain micro-organisms will be missed), analyses of complex real world soil samples can become confounded by dual sampling effects: due to the high spatial heterogeneity of soil biota, each collection of samples will necessarily miss some (unknown) fraction of the "true" community, and stochastic or systematic errors in sequencing success could exacerbate this effect. Nevertheless, sequence approaches are the only feasible way (preferably in combination with methods that address microbial metabolic activities) to get a hand on soil microbiota. As with above-ground animal samples, it should also be tested whether community-wide sequence analysis (DNA barcoding) could be useful to assess soil animal diversity more quickly than classical extraction and subsequent taxonomic sorting by trained specialists. Recent developments in sequencing technology and bioinformatics support the idea that, in the very near future, such molecular approaches will greatly speed up the documentation of 'hidden diversity' in soil. Whether costs can be reduced to a level that these (demanding) methods also can enter into standard monitoring schemes, is not yet clear.

Biodiversity monitoring: terrestrial vs. limnetic systems

Standard methods of microbial ecology can more easily be applied to freshwater rather than soil systems, at least as long as planktonic organisms are concerned. The reason is that

DNA extraction is less complicated and error-prone from aquatic environments. There are also well established monitoring systems (derived from water quality assessments, e.g. in the course of implementing the EU Water Framework Directive) for freshwater fauna and flora, be it planktonic or benthic. Clearly, freshwater systems should be included in biodiversity monitoring programs. In general, many aquatic food-webs are better understood in terms of ecological theory and processes than terrestrial systems. Moreover, many groups that could make up important indicators (like larger animals that shredder biomass input from surrounding terrestrial systems) are very abundant, easily sampled and taxonomically well known. There are also large groups of *citizen volunteers* (e.g. dozens of such initiatives in North America) who are concerned with water quality assessment. These persons could easily be integrated in monitoring networks of large spatial extent and with high temporal resolution. The major challenge in this regard is the development of similarly effective indication and survey systems for tropical streams and still-waters.

Integrating non-professional scientists – *citizen science participation*

Whatever scope and extent any biodiversity monitoring will assume – it is obvious that professional scientists alone will not be able to perform such exercises except for a few selected (and probably not representative) sites of long-term field studies. There are simply too few scientists with appropriate training and expertise, and these cannot be everywhere every time. Hence, any biodiversity monitoring that aims to uncover changes in species presences and abundances at a higher spatial and/or temporal resolution will require the integration of experienced volunteers (*citizen scientists*). There are many mapping and monitoring schemes all over the world, notably for plants, birds, bats but also for many insects (butterflies, grasshoppers, dragonflies, etc.) and other groups of organisms, that draw heavily on this resource of knowledge and participation. For example, most distributional atlases or Red Data Books would not exist were it not for the thousands of volunteers who contributed their observations as data.

In recent years the use of web-resources has far increased and stimulated this mode of participation. Volunteers can directly enter their observations in data bases, and they are rewarded immediately when they see their observations appearing on maps or in diagrams.

The critical issue here is twofold. First, data structures should be as simple and as universal as possible, to allow for data migration between recording systems and comprehensive overarching evaluations. This is an issue of information technology standards, but should no more pose serious challenges. Second, the quality of data entered is an essential pre-requisite for their usefulness in making or testing predictions. Especially in species-rich or otherwise taxonomically complex groups of organisms appropriate mechanisms need to be developed and improved to warrant data quality and to filter out erroneous or suspect data points, preferably to a large degree by use of automated routines. Other means of improving data quality is the restriction of such monitoring efforts to few, easily identified species, to offer support for capacity building and training amongst volunteers, and having data cross-checked by experts before accepting them. Citizen science approaches without appropriate measures of quality control are counter-productive and yield misleading results.

Opportunities for developing citizen participation are obviously more constrained in tropical countries. If not even professional scientists are able to identify most of the species to be encountered, this cannot be achieved by volunteers either. Nevertheless, at least for some groups of organisms (birds, common trees, certain charismatic butterflies or other insects, etc.) public participation can and should be aimed at. The SKBDF recommends that in the countries where DFG-funded coordinated biodiversity projects are still running, opportunities are explored and implemented to improve this type of participation, e.g. through capacity building amongst teachers or through the design of websites that facilitate identification of organisms in countries where identification guides for most organisms are non-existent and too expensive to be distributed as printed books.

Specific recommendations for implementation in Germany

The DFG currently funds integrated biodiversity projects in tropical as well as temperate-zone ecosystems. In the latter regions, the challenges through high species richness are not as extreme as in the tropics. For Germany, many data are available, including distribution data on the occurrence of species, long-term data on changes in the abundance of species, as well as data on specific ecosystem functions and processes. Here, the challenge is rather that data have been collected by a multitude of institutions at different spatial scales and with different methodologies. For example, the Dachverband Deutsche Avifaunisten (DDA) has a monitoring scheme for birds at the national level; the University Kiel is collecting time series data on mammal species under hunting law together with the Landesjagdverband Schleswig-Holstein; some Bundesländer use “biomonitoring” of lichens to monitor air quality. In Germany, the challenge lies in obtaining an overview on data availability, on gaining access to data and on legal issues of data ownership and the permission to use data for scientific purposes. An even greater challenge is making use of the data for answering relevant and timely questions in both basic and applied research. With the development of novel complex statistical techniques, for example structural equation modelling or hierarchical Bayesian modelling, it appears possible that even these patchy, inhomogeneous data sources can be utilized. This approach, nevertheless, requires the identification and formulation of research questions that can be addressed with this type of data; it requires the development of collaborative networks between scientists and the institutions and persons that are data holders. It further requires the appropriate use and further development of the mentioned statistical techniques.

The implementation of a central repository of biodiversity data funded through the DFG could ´play a crucial role in making (and keeping) available primary data for subsequent scientific use. The SKBDF also suggests that ways should be explored to increase the involvement of current data holders, especially at the national level, to participate in exchange and common use of most valuable biodiversity data. Due to its federal organization, Germany currently suffers from the lack of unifying analyses – whereas many of the pertinent data are already out there, but largely inaccessible in a range of uncoordinated repositories.

Concluding remarks

The monitoring of biodiversity in real world (and thus mostly species-rich) communities provides manifold challenges. This paper draws together a couple of critical statements how and why these constraints hinder the systematic assessment of biodiversity, in a manner analogous to more "simple" measurements of physical or chemical attributes of the environment or of parameters derived from remote sensing technologies. It also shows some lines along which this problematic situation can and should be improved. Especially, some research activities are recommended to be intensified, with particular emphasis on the role DFG-funded coordinated biodiversity research in tropical and temperate regions could play in advancing the development of monitoring biodiversity development along with ongoing global climate and land-use change.

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