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The BIOTA Biodiversity Observatories in Africa—a standardized framework for large-scale environmental monitoring

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Abstract The international, interdisciplinary biodiversity research project BIOTA AFRICA initiated a standardized biodiversity monitoring network along climatic gradients across the African continent. Due to an identified lack of adequate monitoring designs, BIOTA AFRICA developed and implemented the standardized BIOTA Biodiversity Observatories, that meet the following criteria (a) enable long-term monitoring of biodiversity, potential driving factors, and relevant indicators with adequate spatial and temporal resolution, (b) facilitate comparability of data generated within different ecosystems, (c) allow integration of many disciplines, (d) allow

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spatial up-scaling, and (e) be applicable within a network approach. A BIOTA Observatory encompasses an area of 1 km^2 and is subdivided into 100 1-ha plots. For meeting the needs of sampling of different organism groups, the hectare plot is again subdivided into standardized subplots, whose sizes follow a geometric series. To allow for different sampling intensities but at the same time to characterize the whole square kilometer, the number of hectare plots to be sampled depends on the requirements of the respective discipline. A hierarchical ranking of the hectare plots ensures that all disciplines monitor as many hectare plots jointly as possible. The BIOTA Observatory design assures repeated, multidisciplinary standardized inventories of biodiversity and its environmental drivers, including options for spatial up- and downscaling and different sampling intensities. BIOTA Observatories have been installed along climatic and landscape gradients in Morocco, West Africa, and southern Africa. In regions with varying land use, several BIOTA Observatories are situated close to each other to analyze management effects.

Keywords Diversity · Global change · Permanent plot · Sampling scheme · Transect · Vegetation

Abbreviations

ALTER-Net	A Long-Term Biodiversity, Ecosystem and Awareness Research Network
BDM	(Swiss) Biodiversity Monitoring
BIOTA	Biodiversity Monitoring Transect Analysis in Africa
CBD	Convention on Biological Diversity
DFG	Deutsche Forschungsgemeinschaft
DIVERSITAS	An International Programme of Biodiversity Science
EBONE	European Biodiversity Observation Network
GEO BON	Group on Earth Observations Biodiversity Observation Network
GEOSS	Global Earth Observation System of Systems
GLORIA	Global Observation Research Initiative in Alpine Environments
ILTER	International Long-Term Ecological Research
ÖFS	(German) Ökologische Flächenstichprobe
ROSELT/OSS	Réseau d'Observatoires de Surveillance Écologique à Long Terme/ Observatoire du Sahara et du Sahel
WMO	World Meteorological Organization

Introduction

Biodiversity loss is one of the most complex challenges for science and society world-wide (Sala et al. 2000; World Resources Institute 2005). Its negative effects on ecosystem services and human welfare are well documented (Dobson et al. 2006; Costanza et al. 2007; Turner et al. 2007). Therefore, the 193 countries that are parties to the Convention on Biological Diversity (CBD) agreed to the political goal of reducing the rate of biodiversity loss by 2010, an ambitious and scientifically problematic goal (Mace et al. 2010). One of the major weaknesses of this "2010 goal" was and still is the inadequate data on changes in biodiversity in space and time. Benchmarking of success or failure of the "2010 goal" is possible

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only for certain aspects of biodiversity. For example, remote sensing techniques allowing the measurement of the change in spatial representation of certain ecosystems (e.g., forests, wetlands), and measurements of population size of some species (mostly large mammals) are amongst the few examples of successful monitoring.

This discussion highlights the need for standardized methods to measure rates of biodiversity change, as mandated by the "2010 goal" (Pereira and Cooper 2006). We point out the difficulty in verifying whether projections of future species losses (Thomas et al. 2004; McClean et al. 2006; van Vuuren et al. 2006; Sommer et al. 2010) accurately depict trends. Additionally, we emphasize that these projections still critically lack empirical baseline data on local patterns of biodiversity and their dynamics and interactions within communities and habitats (Scholes et al. 2008).

The lack of empirical biodiversity observation data is obvious at several levels of complexity; even basic inventories of present (global to local) biodiversity are missing despite their eminent role as baseline and reference data for changes over time. Species richness, the central "currency" for biodiversity (Gaston and Spicer 2005), is reasonably documented at a large scale only (grain = approx. 1,000–100,000 km^2, e.g., Gaston 2000; Mutke and Barthlott 2005), and only for well-studied organism groups like vascular plants and vertebrates. Medium-scale information (grain = approx. 1–100 km^2) on biodiversity is available, but only for selected taxa in some well-studied regions like Europe, while standardized small-scale data (grain = 1 m^2–10 ha) covering larger areas (i.e., spatial extents) remain underutilized (for review, see Dengler 2009b). For the majority of the global surface, and particularly the most biodiverse regions, comparable data are missing even on vascular plants and vertebrates, not to mention the more specious groups of non-vascular plants, invertebrates, fungi, and microbes (constituting 83% of the described species on Earth according to the figures in Lecointre and Le Guyader (2006). Even if such information on local to regional biota were fully available, we would not be able to project reliably the effect of global environmental change on global, regional, or even local biodiversity, owing to a lack of information on the processes driving the changes in patterns of diversity at the community level at different spatial scales.

One of the reasons for this gap of empirical medium and small-scale information is the lack of global or even regional methodological standards in biodiversity research, in particular regarding analyzed spatial scales. As nearly all aspects of biodiversity are scale-dependent (Wiens 1989; Noss 1990; Storch et al. 2007; Goetze et al. 2008; Dengler et al. 2009; see Fig. 1) and ecological processes have cross-scale effects (Carpenter et al. 2006), multi-scale indicators for biodiversity are required. If measured repeatedly, they will provide evidence for the extent and rate of the biological response to environmental change at different spatial scales and thus provide evidence that is required to validate, support, and improve current projections of biodiversity change (Araújo et al. 2005). In analogy to the long history of meteorological monitoring according to standards of the World Meteorological Organization (WMO; see http://www.wmo.int/), which informs climate change projections, standardized biodiversity monitoring is required to inform projections of global biodiversity change.

The need for biodiversity research and monitoring network(s) that develop and implement a concept and methodology for a standardized or at least harmonized design for measurement of biodiversity change within ecosystems and real landscapes has long been understood (Noss 1990; Yoccoz et al. 2001; Balmford et al. 2005; Carpenter et al. 2006; Pereira and Cooper 2006; Grainger 2009). Such a standardized design should be suitable for different biomes, allow spatial up-scaling and long-term monitoring as well as facilitate interdisciplinary approaches within a regional to global network. Various environmental monitoring initiatives have been suggested and implemented, particularly during the last decade in order to understand and quantify environmental changes, e.g., ILTER (Kim 2006), ROSELT/OSS (Aïdoud et al. 2008), GLORIA (Pauli et al. 2004; see "Comparison with other monitoring networks"), RAINFOR (Malhi et al. 2002), and TEAM (see www.teamnetwork.org). More recently, several EU-funded projects (ALTER-Net, see http://www.alter-net.info; EBONE, see http://www.ebone.wur.nl/UK/) have been developed as a response to the need for consolidated biodiversity data. The bioDiscovery Core Project (Ash et al. 2009) of the international DIVERSITAS Program (Loreau and Olivieri 1999) was launched to facilitate the process.

However, in 2000, when the research project BIOTA AFRICA (*Bio*diversity Monitoring *T*ransect *A*nalysis in *Africa*; Jürgens 2004, see http://www.biota-africa.org) initiated a standardized biodiversity monitoring network across Africa, no monitoring design that met all the above-mentioned criteria was available (for details, see "Lessons learned and potential improvements"). BIOTA AFRICA therefore developed and implemented the required standardized design, to be applied along climatic gradients across the African continent, the so-called BIOTA Biodiversity Observatories (further: BIOTA Observatories).

In this article, we describe the BIOTA Observatory design, which so far has been only partially published, mostly in sources not easily or widely accessible (Jürgens 1998, 2006; Schmiedel and Jürgens 2005; Krug et al. 2006). We will focus on the design of the monitoring of vascular plants for which a standardized regular monitoring has been furthest developed and implemented. We then give an overview where BIOTA Observatories have so far been implemented covering major biomes throughout the African continent. Further, we discuss the lessons learned and suggestions for improvements that arose from our practical experience of 9 years of biodiversity monitoring. Finally, we briefly discuss the advantages of the BIOTA Observatory design in comparison to other long-term monitoring frameworks.

Aims and criteria of the BIOTA AFRICA approach

The basic aims of the project BIOTA AFRICA were to provide scientifically sound data on biodiversity, its environmental driving factors, and its changes in time for selected observation sites representing major biomes and ecosystems of the African continent. Such data are needed urgently for ecological research, conservation planning, and as ground-truth data for validations of models and projections. They are thus critical for the development of adaptation and mitigation strategies for resource management under global climate change.

For this purpose, BIOTA AFRICA developed the BIOTA Observatories as a monitoring tool that covers the different levels of complexity (i.e., genes, species, ecosystems) and dimensions (i.e., composition, structure, function and evolution) of biodiversity (sensu Noss 1990; see Fig. 1). The design of these permanent observation sites within typical landscapes should:

- Allow long-term monitoring of biodiversity as well as of indicators and potential driving factors of biodiversity change with adequate spatial and temporal resolution.
- Enable the monitoring of a broad range of different taxa.
- Include measurement of important potential abiotic (e.g., climate, soil characteristics) and biotic (e.g., land use, demography, biotic interactions) drivers of change.
- Analyse several different spatial scales, thus supporting spatial up-scaling.
- Allow comparison of data gained from different biomes, ecosystems, and land use regimes.

Further, the philosophy of BIOTA AFRICA considers as important:

- Integrating approaches of different scientific disciplines (from remote sensing to ground truth, social and natural sciences, empirical and modelling approaches).
- Involving local stakeholders into the development and implementation of the observation program within a participatory process.
- Integrating the BIOTA Observatories into regional to global observation networks, with the aim to implement and adjust the required standards and long-term perspective globally.

BIOTA Observatories meeting these requirements have been established and tested in northern, western and southern Africa along transcontinental transects following major climatic gradients (for details, see "The BIOTA biodiversity

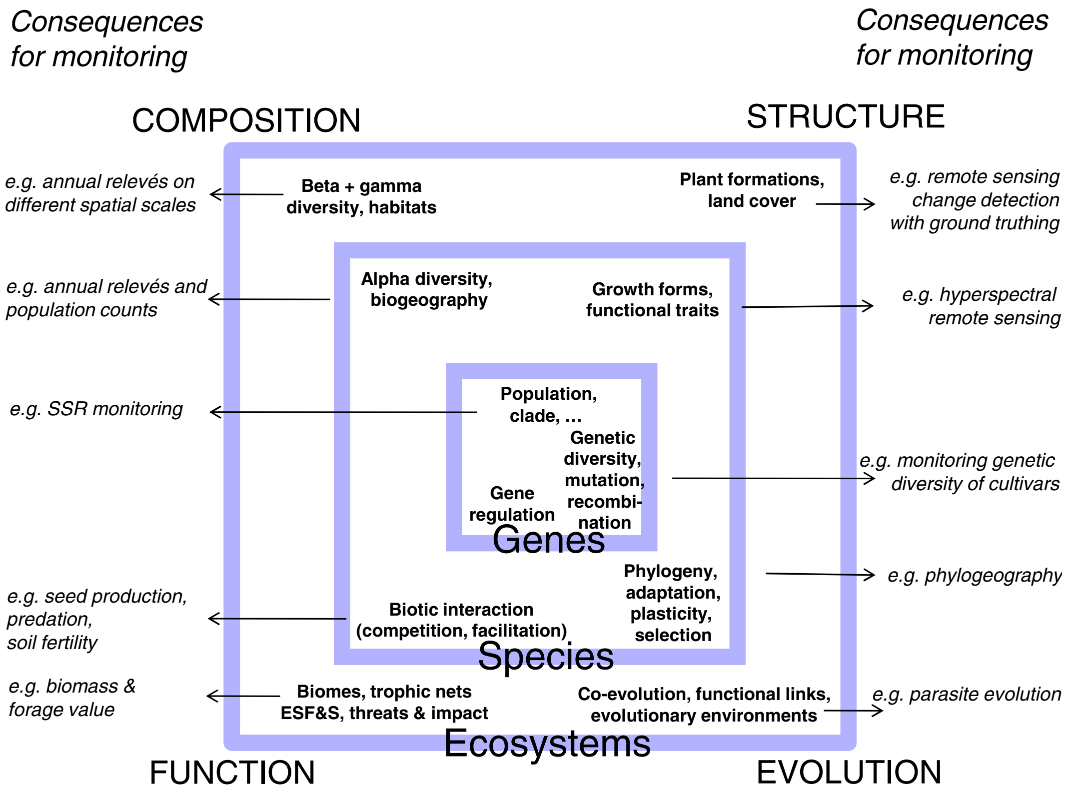


Fig. 1 Levels of complexity (genes, species, ecosystems) and dimensions (composition, structure, function, and evolution) of biodiversity as well as their consequences for the conceptual design of the BIOTA monitoring approach (amended after Noss 1990)

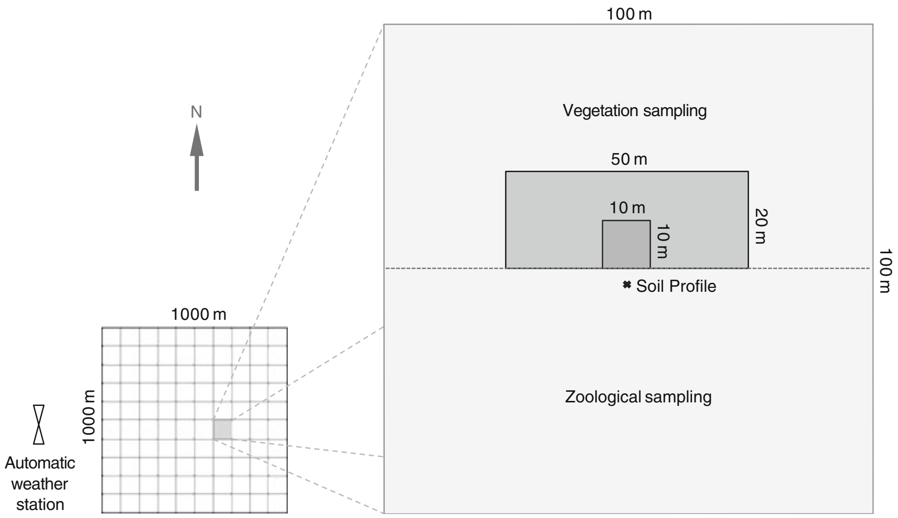
observatories in Africa”). The BIOTA Observatories provide in-situ measured evidence for biodiversity changes and their driving factors across the African continent. The resulting time series of ground-based data are complemented by modern remote sensing-based biodiversity monitoring tools (Oldeland et al. 2010). While the BIOTA Observatory data are critical to provide ground-truthing for the remote-sensing monitoring, the latter can help to extrapolate the information into a larger domain (Duro et al. 2007). For a better understanding of the processes that drive spatial and temporal patterns of biodiversity, BIOTA AFRICA also established several “auxiliary observatories” of deviating design, where specific observation tasks or specific experiments were carried out (e.g., Jürgens 2006; Musil et al. 2009).

Sampling layout of the BIOTA Biodiversity Observatories

Spatial layout

A BIOTA Observatory encompasses an area of 1 km^2 (1,000 m × 1,000 m) with boundaries oriented along cardinal directions (Fig. 2). The spatial layout and subplot numbering of BIOTA Observatories is mirrored across the equator. The 1-km^2 area is divided into 100 1-hectare plots of 100 m × 100 m, with corner points well marked and geo-referenced. The hectare plots are numbered from 00 to 99 starting in the upper left corner (i.e., the North-West corner in the southern hemisphere) and running from the left (West) to the right (East) and pole-wards through the BIOTA Observatory. The hectare plots constitute

Fig. 2 Schematic layout of a BIOTA Observatory (in the southern hemisphere) and arrangement of different sampling areas within one of the hectare plots

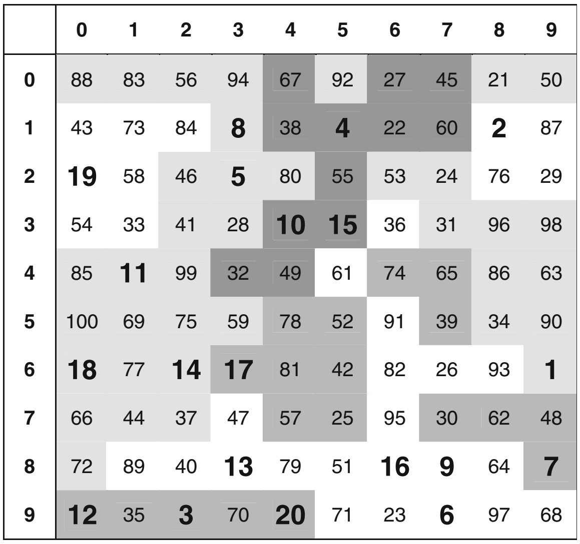


the largest replicated sampling unit within the BIOTA Observatory.

In general, the number of investigated hectare plots should be large enough to allow a statistically robust description of the BIOTA Observatory. However, within the multidisciplinary team, one problematic issue became evident. The activities of the involved disciplines had to be aligned spatially in order to achieve the best possible integration of data, while the risk of artefacts caused by the various scientific activities had to be minimized. Our procedures for selecting the hectare plots and assigning areas within hectare plots for different purposes aim at the best possible compromise between the two conflicting aims.

Some of the disciplines apply techniques that are too laborious to allow investigation of a larger number of hectare plots. This fact could result in spatial "fragmentation" of activities and hence cause a lack of integration of these disciplines and their respective organism groups. To overcome this problem, all disciplines agreed to do their sampling work on hectare plots following a predefined sequence. This sequence is defined by a ranking procedure, which assigns to each hectare plot one of the ranks 1 to 100 (Fig. 3).

Complete randomization of plots in heterogeneous environments involves the risk of disregarding rare habitat types (Wildi 1986; Ruxton and Colegrave 2006; Roleček et al. 2007). To ensure a representative randomized sampling, we employed a stratified sampling design (Wildi 1986) and developed a ranking method based on the d'Hondt divisor rules procedure (Balinski and Ramirez 1999; Palomares and Ramirez 2003; Taagepera and Shugart 1989). For this purpose,



	0	1	2	3	4	5	6	7	8	9
0	88	83	56	94	67	92	27	45	21	50
1	43	73	84	**8**	38	**4**	22	60	**2**	87
2	**19**	58	46	**5**	80	55	53	24	76	29
3	54	33	41	28	**10**	**15**	36	31	96	98
4	85	**11**	99	32	49	61	74	65	86	63
5	100	69	75	59	78	52	91	39	34	90
6	**18**	77	**14**	**17**	81	42	82	26	93	**1**
7	66	44	37	47	57	25	95	30	62	48
8	72	89	40	**13**	79	51	**16**	**9**	64	**7**
9	**12**	35	**3**	70	**20**	71	23	**6**	97	68

Fig. 3 Example of the grid system of a BIOTA Observatory (S08, Niko North, Namibia, see Table 2) with ranking numbers. Line and row numbers are given at the *left* and *top* margins, respectively; the plot numbers are derived by the combination of the line number (*first figure*) and the row number (*second figure*). Different shades of grey represent the four habitat types distinguished on this BIOTA Observatory (*white* stony plain; *light grey* wash (plain); *medium grey* stony slope; *dark grey* wash-rivier). The numbers of the 20 highest ranked grids (those on which vascular plants are analyzed) are printed in *bold letters*

each hectare plot is characterized by a combination of its predominant vegetation and geomorphological structures, further referred to as "habitat type". The basic principle of the d'Hondt divisor method is to divide the number of hectare plots of each stratum (i.e., habitat type) by natural numbers (1, 2, 3, 4, ... *n*). The resulting quotients of all habitat types are sorted in descending order. The highest quotient and therefore its habitat type would be allocated to rank number 1, the habitat type of the second quotient would be ranked second, and so on. With this method, a sequence of the habitat types can be compiled according to their real proportions.

Deviating from the original method of d'Hondt, we up-weighed the proportion of rare habitat types by using the square root of habitat frequency as basis for the determination of the ranking order. This modification has the effect of positioning the hectare plots of less common habitat types on higher ranks. This effect is desirable because it ensures a minimum of replicates even for rare habitat types in small sample sizes. Given the allocation of the habitat types, the rank number of the hectare plots is selected randomly within each. This results in a ranking of all hectare plots, each with a ranking number between 1 and 100. Figure 3 shows an example of the grid structure and ranking order of a BIOTA Observatory. Besides achieving representativeness among the plots sampled, the application of this ranking method allows for interdisciplinary studies as the same ranking, and therefore the same sequence of plots, is applied across all disciplines.

Each discipline defines the number of hectare plots to be analyzed (x) and then carries out its research on the hectare plots of ranks 1 to x. Accordingly, the highest-ranked hectare plots are jointly sampled by all disciplines working on the BIOTA Observatory. This obviously involves the risk of disturbance, interference, and artefact. To reduce such problems, experimental studies are allowed only outside the 1-km^2 boundary of the BIOTA Observatory and the researchers are asked to walk primarily along the lines from corner to corner of the hectare plots and leave its central parts undisturbed. Further, the more intensive-use study sites of the different disciplines are spatially separated within each hectare plot. The zoological trapping area (often involving digging or interference with plants) on the one hand are placed in the pole-ward halves of the hectare plots whereas the area for botanical small-scale monitoring as well as lichenological and microbiological sampling are arranged in its equator-ward part (see Fig. 3). Similarly, the standardized position of the destructive soil profile is set 4 m pole-ward of the centre point of the hectare (Fig. 3).

Sampling of vascular plants

The vegetation monitoring is done on sets of three nested plots, with plot sizes following a geometric series (100 m^2, 1000 m^2, and 10,000 m^2). The plots are permanently marked with common metal fencing poles or buried magnets. While the 100- and 10,000-m^2 plots are squares, the 1000-m^2 plots have a rectangular shape of 20 m × 50 m (Fig. 2). These plot dimensions are frequently used among vegetation and biodiversity studies worldwide (Shmida 1984; Peet et al. 1998; Stohlgren 2007) and are regularly applied for vegetation mapping in Namibia (Strohbach 2001; Hüttich et al. 2009). The type of sampled data differs between the different plot sizes (see Table 1). For the estimation of cover, the vegetation is divided in vertical strata according to standardized height categories. Total species cover as well as cover of each vertical layer is estimated as accurately as possible in percent. It should be stressed that deviating from phytosociological tradition, where cover values below 1% are usually not further differentiated (e.g., Dierschke 1994), accuracy up to two decimal points is advisable for the estimation of very low cover values as they frequently occur in arid environments (see similar

Table 1 Types of vascular plant data sampled within the different plot sizes

Plot size	Presence	Cover	Abundance
100 m^2	X	X	X[a]
1,000 m^2	X	X	
10,000 m^2 = 1 ha	X		

[a] Only perennial plant species may be included, depending on limitations of data gathering. In a few BIOTA Observatories with relatively dense vegetation, graminoid species were excluded from abundance counts

recommendation in Pauli et al. 2004). Each plot is photographed in a standardized way for visual documentation.

Individual-based quantitative and spatial monitoring allows the recording of population dynamics and thus a highly sensitive set of indicators for change. Such a monitoring is generally applied in the 1000-m^2 and 100-m^2 plots of highest rank. There, each individual of all occurring perennial species (in the 1000-m^2 plot only for nanophanerophytes and larger life forms) is measured (i.e., height: difference between ground to highest living part of the plant; first diameter: longest diameter; second diameter: longest diameter orthogonal to first diameter). Additionally, its relative position is drawn on a plot map or registered in a 0.5-m grid. In humid biomes of West Africa, woody species regeneration is also monitored in plots of 25 m^2 size where size (height, diameter) and position of each woody plant individual is recorded.

All vegetation monitoring is repeated at regular intervals (i.e., annually in arid and semi-arid regions and typically in three-year intervals in tropical regions) and at about the same time of the year during the phenological phase of maximal vegetation development.

Sampling other organism groups

Within BIOTA AFRICA, many other organism groups have been sampled with standardized designs on some or on nearly all BIOTA Observatories, with the sampling design and intensity adapted according to disciplinary needs. In BIOTA Southern Africa, for example, inventories have included lichens on all substrata (Zedda et al. 2008, 2011) and biological soil crusts with their constituent organisms such as cyanobacteria and algae (Büdel et al. 2009). Further, fungi, ground-dwelling beetles (Henschel et al. 2010), termites (Vohland and Deckert 2005), ants, butterflies and moths, as well as small mammals (Giere and Zeller 2005) have been recorded according to uniform sampling protocols. The detailed description of the specific sampling methods is not a subject of the present publication (for details, see Haarmeyer et al. 2010).

Soil studies

Soil studies are conducted in the ranking sequence and at the pre-defined position within the hectare plots (Fig. 2); for details, see Petersen (2008) and Petersen et al. (2010). A soil profile of 0.6–1.2 m depth is described with respect to the following parameters: stratification, texture, rock fragments, color, humus content, lime content, soil and surface structure, crusting, bulk density, penetration resistance, and distribution of roots (FAO 2006). Each profile is documented with a photograph of the profile and the surrounding habitat.

Mixed samples for laboratory analyses are taken from all horizons of the profile. Additionally, defined sample volumes are taken using core samplers in order to determine the bulk density. The depth of the individual samples corresponds to horizon boundaries. If there is no distinct horizon in the topsoil, the depth of the first sample is 10 cm. While assessing the soil profile, the soil material is deposited on a large sheet. The profile is refilled after sampling to minimize disturbance of the site and its vegetation. The profiles are described according to widely accepted standards (e.g., FAO 1990; Schoeneberger et al. 2002) and then classified according to a globally applicable system (IUSS Working Group WRB 2006).

Weather stations

In close vicinity to each BIOTA Observatory, an automatic weather station is installed to relate the time series of biodiversity data to local weather conditions and long-term climatic trends. Measured weather parameters include rainfall, air temperature, relative air humidity, leaf wetness, solar radiation, wind speed, and direction.

Additional data on driving factors

In BIOTA AFRICA, the ecological monitoring on the BIOTA Observatory was complemented by studies on economic, legal, administrative, social, and cultural driving factors of the local to regional land use (e.g., Falk 2008; Pröpper 2009;

Vollan 2009; Vollan et al. 2009). Additional studies, which are located in the vicinity of the BIOTA Observatory, complement the monitoring data by experimental approaches (e.g., grazing exclosures or active restoration treatments), to study ecological processes underlying the observed changes. These studies do not use the BIOTA Observatory design but relate to respective biodiversity baseline data or infrastructure (e.g., weather stations).

The BIOTA Biodiversity Observatories in Africa

Implementation

BIOTA Observatories form the “backbone” of the large African–German, interdisciplinary research project BIOTA AFRICA. Since 2001, they have been arranged along mega-transects that follow important large-scale environmental gradients in Africa (Fig. 4), thereby covering many major ecosystem types of the biomes sampled

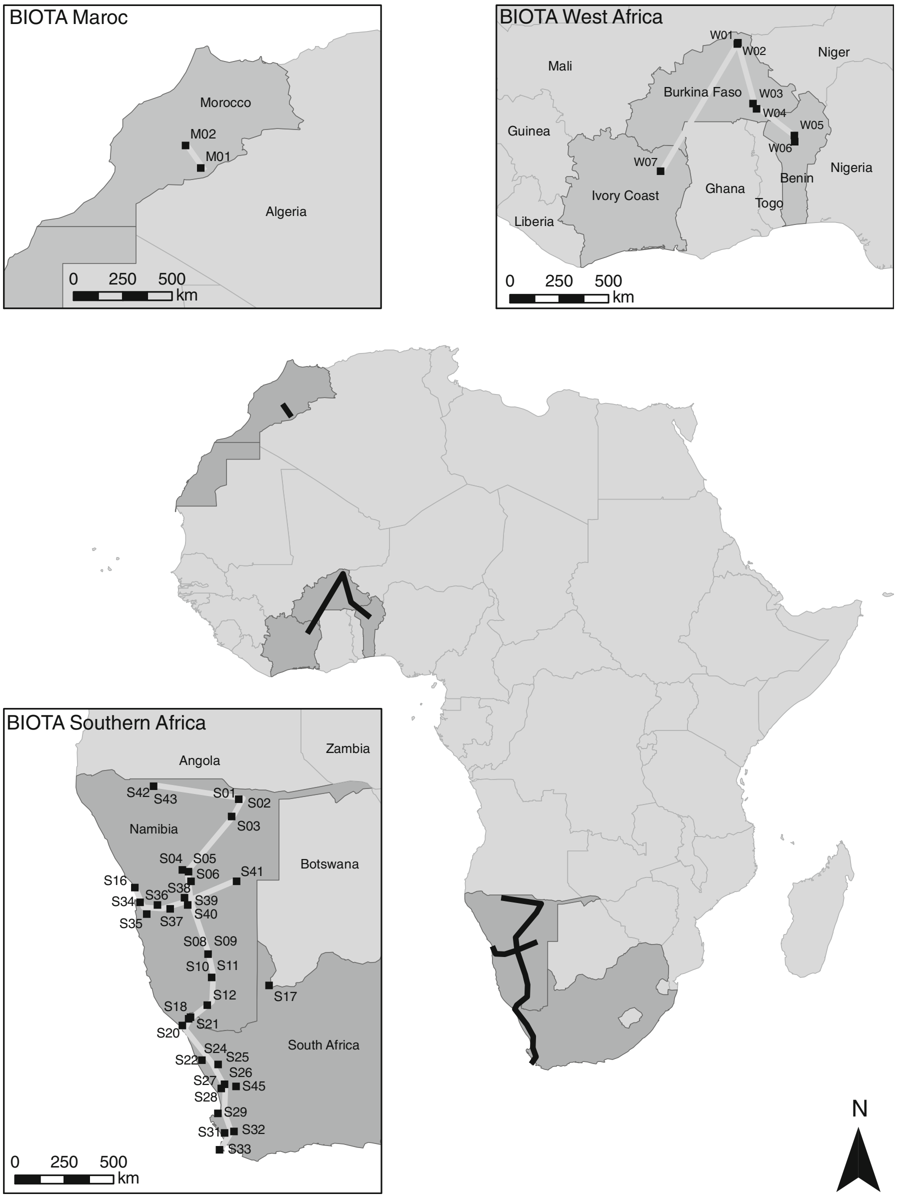


Fig. 4 Map of the established BIOTA Observatories in Africa (as of 4 April 2010). For further information on the individual BIOTA Observatories, see Table 2

Table 2 Overview of the established BIOTA Observatories in Africa (as of 4 April 2010) with their main characteristics

Observatory no.	Observatory name	Country	Primary administrative unit	Locality	Altitude (m a.s.l.)	Biome	Soil data	Years with vascular plant data
BIOTA Maroc								
M01	El Miyit	Morocco	Souss-Massa-Draâ	Tizi n Tafilalet	1869	Saharan Semidesert	–	2002, 2003, 2005–2009
M02	Taoujgalt	Morocco	Souss-Massa-Draâ	Taoujgalt	736	Ibero-Mauritanian Sagebrush Steppe	–	2002–2005, 2008, 2009
BIOTA West Africa								
W01	Yomboli	Burkina Faso	Sahel	Yomboli	286	Sahel Grass- and Shrubland	–	2001, 2002
W02	Kolel	Burkina Faso	Sahel	Kolel	295	Sahel Grass- and Shrubland	–	2001
W03	Kikideni	Burkina Faso	Est	Kikideni	304	North Sudanian Savanna	x	2001, 2003
W04	Natiabouani	Burkina Faso	Est	Natiabouani	258	North Sudanian Savanna	x	2001–2003
W05	Alibori	Benin	Atacora	Péhunco	297	South Sudanian Savanna	x	2002
W06	Terroire Villageois	Benin	Atacora	Péhunco	327	South Sudanian Savanna	x	2002
W07	Comoé	Ivory Coast	Zanzan	Parc National de la Comoé	220	South Sudanian Savanna	–	2001
BIOTA Southern Africa: North–South Transect, Namibia								
S01	Mile 46	Namibia	Kavango	near Cove	1180	Southern African Woodland Savanna	x	2001–2003, 2005–2009
S02	Mutompo	Namibia	Kavango	near Cove	1180	Southern African Woodland Savanna	x	2001–2003, 2005–2009
S03	Sonop	Namibia	Otjozondjupa	near Maroelaboom	1236	Southern African Woodland Savanna	x	2001–2003, 2005, 2006, 2008, 2009
S04	Toggekry	Namibia	Otjozondjupa	Omatako Ranch	1519	Southern African Thornbush Savanna	x	2001–2009
S05	Otjiamongombe	Namibia	Otjozondjupa	Erichsfelde	1495	Southern African Thornbush Savanna	x	2004–2009
S06	Okamboro	Namibia	Otjozondjupa	Ovitoto	1490	Southern African Thornbush Savanna	x	2004–2009
S08	Niko North	Namibia	Hardap	near Gibeon	1070	Nama Karoo	–	2001, 2002, 2004, 2006–2009
S09	Niko South	Namibia	Hardap	near Gibeon	1076	Nama Karoo	–	2001, 2002, 2004, 2006–2009
S10	Gellap Ost	Namibia	Karas	Keetmanshoop	1099	Nama Karoo	x	2001–2009
S11	Nabaos	Namibia	Karas	Keetmanshoop	1045	Nama Karoo	x	2001–2009
S12	Karios	Namibia	Karas	Karasburg	909	Nama Karoo	x	2001–2009

S16	Wlotzkasbaken	Namibia	Erongo	Swakopmund	73	Namib Desert	x	2001–2003, 2005, 2010
S42	Ogongo	Namibia	Omusati	Ogongo	1103	Southern African Woodland Savanna	x	2007–2009
S43	Omano go Ndjamba	Namibia	Omusati	Ogongo	1100	Southern African Woodland Savanna	x	2007–2009
BIOTA Southern Africa: North–South Transect, South Africa								
S17	Alpha	South Africa	Northern Cape	Askham	896	Southern African Thornbush Savanna	x	2002, 2003, 2005–2007
S18	Koeroegavvlakte	South Africa	Northern Cape	Sendelingsdrif	635	Succulent Karoo	x	2001–2009
S20	Numees	South Africa	Northern Cape	Sendelingsdrif	362	Succulent Karoo	x	2001–2003, 2006
S21	Grootderm	South Africa	Northern Cape	Alexander Bay	193	Succulent Karoo	x	2001–2006, 2008
S22	Soebatsfontein	South Africa	Northern Cape	Soebatsfontein	392	Succulent Karoo	x	2001–2009
S24	Paulshoek	South Africa	Northern Cape	Leliefontein	1048	Succulent Karoo	x	2001–2009
S25	Remhoogte	South Africa	Northern Cape	Leliefontein	1027	Succulent Karoo	x	2001–2009
S26	Goedehoop	South Africa	Western Cape	Van Rhynsdorp	245	Succulent Karoo	x	2001–2009
S27	Ratelgat	South Africa	Western Cape	Van Rhynsdorp	239	Succulent Karoo	x	2001–2009
S28	Moedverloren	South Africa	Western Cape	Vredendal	140	Succulent Karoo	–	2001–2009
S29	Rocherpan	South Africa	Western Cape	Piquetberg	35	Fynbos	–	2005
S31	Riverlands	South Africa	Western Cape	Malmesbury	140	Fynbos	–	2004, 2008, 2009
S32	Elandsberg	South Africa	Western Cape	Wellington	95	Fynbos	x	2009
S33	Cape of Good Hope	South Africa	Western Cape	Table Mountain National Park	83	Fynbos	x	2008, 2009
S45	Nieuwoudtville	South Africa	Northern Cape	Nieuwoudtville	722	Fynbos	–	2007
BIOTA Southern Africa: East–West Transect, Namibia								
S34	Kleinberg	Namibia	Erongo	Walfis Bay	188	Namib Desert	–	2010
S35	Gobabeb	Namibia	Erongo	Gobabeb	419	Namib Desert	–	2004
S36	Ganab	Namibia	Erongo	Namib-Naukluft Park	995	Namib Desert	–	2010
S37	Rooisand	Namibia	Khomas	Rooisand Desert Ranch	1160	Southern African Thornbush Savanna	–	2005
S38	Claratal	Namibia	Khomas	Windhoek	1865	Southern African Thornbush Savanna	x	2005, 2007, 2009
S39	Narais	Namibia	Khomas	near Rehoboth	1624	Nama Karoo	x	2004–2009
S40	Duruchaus	Namibia	Khomas	near Rehoboth	1614	Nama Karoo	x	2004–2009
S41	Sandveld	Namibia	Omaheke	near Drimiopsis	1523	Southern African Thornbush Savanna	x	2005, 2008, 2009

More detailed information is available in Online Resource 1

(Fig. 4). They are situated within relatively homogeneous sites representative of the respective region. Mostly, they correspond to zonal vegetation, i.e., vegetation that is mostly determined by regional climate and hardly modified by soil and geomorphological properties or human influence (see Walter and Breckle 1983). Where land use differed significantly within a region (e.g., regarding grazing intensities), two or more BIOTA Observatories were placed close to each other to cover a wider section of this variability.

Up to now, 46 BIOTA Observatories (Fig. 4, Table 2, Online Resource 1) have been established and studied by researchers from approximately 50 institutions from six African countries (Benin, Burkina Faso, Ivory Coast, Morocco, Namibia, South Africa) and Germany. The BIOTA Observatories belong to BIOTA Maroc ($n=2$), BIOTA West Africa ($n=7$), and BIOTA Southern Africa ($n=37$). Year of implementation, frequency of repetition, and intensity of sampling varied depending on project priority settings of the respective BIOTA Observatory and technical constraints (Table 2, Online Resource 1). The monitoring data gained are stored centrally at the BIOTA Data Facility of the BIOTA Head Office at the Biocentre Klein Flottbek, University of Hamburg, Germany (Muche et al. 2010). Data storage employs BIOTABase, a software specifically designed to store, process, and facilitate analyses of long-term, multi-scale biodiversity data (http://www.biota-africa.org/biotabase_a.php; see Muche and Finckh 2009). The vegetation databases of the three regional BIOTA projects are all registered in the Global Index of Vegetation-Plot Databases (GIVD; Dengler et al. 2011; see www.givd.info), with the unique IDs AF-MA-001 (Morocco), AF-00-001 (West Africa), and AF-00-003 (Southern Africa). The data are available on request for scientific research purposes.

Results achieved

So far, soil (e.g., Mills et al. 2006; Petersen 2008; Medinski et al. 2010) and biodiversity patterns and processes along climatic gradients (e.g., Uhlmann et al. 2004; Zedda and Rambold 2004; Giere and Zeller 2005; Vohland and Deckert 2005; Büdel et al. 2009; Hahn-Hadjali et al. 2006; Wittig et al. 2007; Schmidt et al. 2010; Schmiedel et al. 2010a; Zedda et al. 2011) as well as between different land use types (e.g., Hoffmann and Zeller 2005; Vohland et al. 2005; Koulibaly et al. 2006; Mayer et al. 2006; Pufal et al. 2008) have been analyzed with data from the BIOTA Observatories. Time series provided insights into population and ecosystem dynamics (Jürgens 2006). Data from the BIOTA Observatories and their surroundings were fed into ecological models on maintenance of biodiversity (Reineking et al. 2006), gene flow in fragmented landscapes (e.g., Blaum and Wichmann 2007), and hydrological processes (Popp et al. 2009a, b; Tietjen et al. 2010). Many more analyses of the African BIOTA Observatory data are in progress, in particular, on biodiversity patterns and their drivers at different spatial scales across the African continent as well as on nine-year time series of in-situ monitoring data.

Lessons learned and potential improvements

Over a period of 9 years, the BIOTA Observatory approach has been applied in various locations and biomes throughout the African continent, involving numerous scientists of different disciplines. Here, we report practical hints, and suggestions for potential improvements.

Ranking system

For practical reasons, in southern Africa the habitat classification for each single BIOTA Observatory, which was required for the ranking at the beginning of the project, was carried out by different scientists from various disciplines. Due to the number of people involved with differing disciplinary perspectives and due to the wide variety of biomes covered, the classifications achieved are appropriate for the respective BIOTA Observatory but hardly support habitat-specific comparisons along the entire southern Africa transects. For future applications, we suggest a priori agreement on a list of clearly defined, transect-wide applicable habitat types as has been done in West Africa.

Further, the square-root weighting of the habitat types within the ranking procedure might be worth reconsidering. It indeed ensures the inclusion of rare habitat types in the sampling but at the same time complicates the derivation of parameter means for a whole BIOTA Observatory and causes problems in statistical inference (e.g., Botta-Dukát et al. 2007; Lájer 2007). From a statistical point of view, it might be favorable to use an unmodified d'Hondt approach to determine the hectare plots to be sampled for the overall characterization of a BIOTA Observatory and to complement this basic sampling—where necessary—with additional hectare plots of rare habitats. The latter could be used for between-Observatory comparisons within transect-wide accepted habitat types, while the mean values calculated without these "additional" hectare plots are unbiased spatial means and thus allow statistical comparison between whole BIOTA Observatories.

Spatial scales

The design of the BIOTA Observatories is inherently multi-scaled because the analysis of biodiversity at multiple spatial scales is fundamental for the understanding of patterns and their driving factors (see "Introduction"). For example, species inventories of vascular plants were explicitly sampled at 100-, 1,000-, and 10,000-m^2 scales, and are available as cumulative data of the 20-ha plots sampled plus occasional observations on the 1-km^2 scale. As the deviation from the square shape at one of the spatial scales (20 m × 50 m) causes difficulties in analyses such as species–area relationships (Stohlgren 2007; Dengler 2008), future implementations should consider using square-shaped plots throughout (see case study in Namibia by Peters 2010). A square shape also would better align with remote-sensing data, which uses square pixels (Alexander and Millington 2000; Richards and Xiuping 2006).

Regarding the sampling of the hectare plots, it turned out that the time needed for complete sampling of vascular plant species on an entire hectare plot often exceeded the allocated time-frame, especially for BIOTA Observatories with relatively dense vegetation. Therefore, for future implementation, we suggest assigning sufficient time and effort that allows for comprehensive sampling or, alternately, sampling the 1-ha scale only for a subset of hectare plots.

As the BIOTA Observatory spatial layout is designed to allow for unlimited up- and downscaling of plots, the addition of smaller plot sizes (e.g., 10, 1, 0.1, 0.01 m^2) could easily be accomplished and has already been tested on single BIOTA Observatories (e.g., Peters 2010). The implementation of these small plots sizes with some replication within the hectare plots (see Shmida 1984; Stohlgren et al. 1995; Peet et al. 1998; Dengler 2009b) as a general standard, would add valuable information with little additional effort. This could, for example, characterize β-diversity via the z-values of the species–area relationship, or allow the extrapolation of species richness to larger areas (e.g., Dengler 2009a; Dengler and Oldeland 2010). The need for a stronger focus on smaller plot sizes was also identified by researchers working in ecosystems with high vegetation density and species richness at small spatial scales (humid biomes of West Africa). On the other hand, larger plot sizes (e.g., 10 and 100 km^2) might be appropriate for the sampling of some highly mobile animals (e.g., large mammals, dragonflies), presently not well covered by the BIOTA Observatory design.

Representativeness

At the start of the BIOTA AFRICA project, the BIOTA Observatories as monitoring tools and thus indicators for biodiversity change were placed at sites that were regarded as representative for the larger landscape. However, as a tool for assessing biodiversity patterns at different spatial scales in the landscape, the density of BIOTA Observatories should be further increased in order to document spatially restricted patterns and processes within a network of BIOTA Observatories. The representativeness within the square kilometer was achieved with the ranking system. However—under shifting cultivation or fire events—a hectare plot may change within a year from semi-natural vegetation to an arable field. For within-Observatory data, such spatio-temporal changes do not at all invalidate the

BIOTA Observatory design, but on the other hand, the (stratified) random design actually allows the documentation of such small-scale patterns and determination of their frequency and their causes (see detailed discussion in Dengler 2009b). However, in BIOTA Observatories with particularly high spatio-temporal variability, it might be necessary to sample more than the usual 20 hectare plots in order to determine patterns and processes with sufficient accuracy and resolution.

Field sampling

From BIOTA fieldwork, several practical hints emerged that might be helpful for future researchers. The size and type of the marking material for the plots should be adjusted to the environment: poles can become overgrown by vegetation if too short; while other poles might be removed by passers-by or run over by ranging animals (e.g., cattle, elephants). Searches for "lost" poles can cost precious time. In areas where marking material might become lost, exact coordinates (taken with differential GPS) for all corners of each plot are critical for replacing the poles at their exact position. For some Observatories near the sea, a rust-resistant form of marking material is recommended. For the annual monitoring of vascular plant vegetation, cumulative species inventories per plot as derived from the previous years' datasets were copied into the field data sheets. This reduced nomenclatural inconsistency between the years and guaranteed consistency in the use of unavoidable "field names" for species in regions where the flora is less well known. For the assessment of the nested vegetation plots within a hectare, it proved to be efficient to start with the smallest plot and then to continue with the next larger sizes. Another important aspect when different observers are involved over time is to standardize methods of cover estimation as far as is possible. Calibration of estimates between different observers before the work starts would be ideal.

Determination, taxonomy, and databasing

Even in industrialized countries where biodiversity is generally well-documented, it is not trivial to achieve a consistent taxonomy of plants and animals in databases with multiple contributors (Berendsohn 1997; Jansen and Dengler 2010). However, this task becomes much more troublesome in transnational projects (with different national checklists) within regions where a large proportion of the flora and fauna is still awaiting classification or at least is not covered in identification keys. This underscores the need for voucher specimens, which must be identified later and archived properly, a time-consuming process. The delay in identification may also cause temporary "inflation" of taxon numbers in the joint database due to inconsistent use of preliminary field names for unidentified species.

Time effort

Generally, the workload for biodiversity monitoring varies strongly between organism groups and biomes. To give an idea of the time actually needed, we refer again to our experiences from the monitoring of vascular plants. One hectare with three nested plots of 100 m^2–10,000 m^2), sampled according to the BIOTA standards (see "Aims and criteria of the BIOTA AFRICA approach") by one researcher, required between one (Namib Desert) and five or more hours (species-rich plots in the Succulent Karoo, southern African Savanna or Fynbos Biomes). Individual-based monitoring required between one (dwarf shrub-dominated habitats in southern Morocco) and more than three working days (dense savanna vegetation in West Africa) per plot. The time effort strongly increases with the size of the plot. Thus, vegetation surveys on 1,000 m^2 take much longer due to the structural complexity and size of the plot, and the estimated cover values are less reliable than on 100 m^2. For the same reason, the species inventories per hectare plot are likely to be incomplete in many cases (Peters 2010). In comparison, Dolnik (2003) reports that an experienced botanist needs up to 14 h to compile a complete species list for a 900-m^2 plot in structure-rich habitats even in temperate Europe despite the limited and well-known flora there.

As a consequence of the aspects mentioned, we recommend that for monitoring vascular plants manpower allocated per BIOTA Observatory should be increased, the number of monitored plots per plot size reduced, or the temporal frequency of monitoring adapted. However, arid and semi-arid biomes with high inter-annual variability of rainfall require annual monitoring in order understand the response of plant populations to various driving factors (climate vs. land use). In tropical biomes with less variable rainfall patterns, monitoring at lower frequencies (e.g., every 3 years) may be sufficient. Further, it might be worth considering carrying out individual-based monitoring in several smaller rather than one larger plot.

Institutional implementation

The practical experience from a research project with temporarily employed project staff (primarily Ph.D. students) for the monitoring work reveals that changes in personnel were the major source of inconsistency in monitoring data. Further, BIOTA AFRICA, which was both a research and a monitoring project, faced the problem that research, which is evaluated based mainly on short-term publication output, and monitoring, whose value increases with the number of consistent datasets over large spatial and temporal scales, often require different sampling approaches. As the potential publication output of such large-scale, medium- to long-term monitoring typically is beyond the time available to individual researchers, there tends to be a conflict between the researcher's short-term need for scientific output and the project's need for time-consuming long-term monitoring data. This also is the reason why the long-term monitoring on the Observatories only played a minor role in the academic capacity development (i.e., involvement of Ph.D. candidates or Postdocs) at the African research institutes. As a consequence, we recommend employing permanent staff for the monitoring fieldwork.

In order to support the time-consuming fieldwork on the BIOTA Observatories, BIOTA Southern Africa employed at full-time and trained eight members of local land user communities as BIOTA para-ecologists. This turned out to be a promising approach: the para-ecologists' support of the biodiversity monitoring activities was highly valuable, but they were also invaluable in facilitating the communication of research findings with the local stakeholders (Araya et al. 2009; Schmiedel et al. 2010b).

Also for data storage and maintenance permanent staff should be responsible as it requires infrastructure and institutional continuity that go far beyond the resources of typical projects with limited funding periods. In addition to the local hosting and processing of the data, permanently implemented central data facilities should guarantee good long-term data quality and security (see also Scholes et al. 2008).

Comparison with other monitoring networks

Meanwhile, various biodiversity monitoring initiatives have emerged as a result of the ongoing debate on global biodiversity decline (Heywood and Watson 1995; Sala et al. 2000; World Resources Institute 2005), most of them during the last decade. Four important initiatives that, like BIOTA, aim at facilitating long-term in-situ monitoring of terrestrial biodiversity, are presented in Table 3 and are compared with the BIOTA Observatories: i.e., ILTER = *I*nternational *L*ong-*T*erm *E*cological *R*esearch (Kim 2006), ROSELT/OSS = *R*éseau d'*O*bservatoires de *S*urveillance *É*cologique à *L*ong *T*erme/ *O*bservatoire du *S*ahara et du *S*ahel (Aïdoud et al. 2008), GLORIA = *G*lobal *O*bservation *R*esearch *I*nitiative in *A*lpine Environments (Pauli et al. 2004, 2009), and the DFG Biodiversity Exploratories (Fischer et al. 2010). Some others have recently been reviewed by Dengler (2009b), namely the European forest monitoring (e.g., Aamlid et al. 2007), the Swiss Biodiversity Monitoring (BDM; e.g., Hintermann et al. 2000), and the German "Ökologische Flächenstichprobe" (ÖFS; e.g., Hoffmann-Kroll et al. 2000). As required by the CBD, most other countries have implemented some kind of national biodiversity monitoring (see Bischoff and Dröschmeister 2000), but there is little standardization among countries, and comparability of data is thus low. In Europe, as a response to this lack, the EU-funded projects EBONE

Table 3 Comparison of major long-term monitoring frameworks with the BIOTA Observatories (as of 4 April 2010)

	BIOTA Observatories	ILTER (International Long Term Ecological Research)	ROSELT/OSS (Réseau d'Observatoires de Surveillance Écologique à Long Terme/Observatoire du Sahara et du Sahel)	GLORIA (Global Observation Research Initiative in Alpine Environments)	DFG Biodiversity Exploratories
Objective	Analysing effects of climate and land use changes on biodiversity	Network of 32 national networks that comprise any kind of long-term ecological monitoring sites	Tackling the causes and effects of desertification around the Sahara.	Assessment of climate change effects on mountain environments	Open research platform for studies dealing with: • The understanding of the relationship between biodiversity of different taxa and levels • The role of land use and management for biodiversity • The role of biodiversity for ecosystem processes
Disciplines	Botany (vascular plants, lichens), zoology (various taxa), soil sciences, climatology, remote sensing, socio-economy	Not standardized, but mostly botany, zoology, soil sciences, nutrient cycling, socio-economy	Botany, zoology, geomorphology, soil sciences, hydrology, climatology, agronomy, (e.g., soil, climate)	Botany (vascular plants obligatory, bryophytes and lichens optional), abiotic environment	Botany (vascular plants, bryophytes, lichens; including genetics), zoology (various taxa), mycology, microbiology, soil sciences, ecosystem pools and fluxes, remote sensing
General sampling design	1 km^2, subdivided into 100 1-ha plots, of which 20 are selected according to a stratified-random procedure; within these, the smaller plots are nested	Not standardized	Three-scale sampling: administrative unit, exploitation unit plot or herd	A site is constituted by at least four mountain summits of different altitude in the same region; for each of the summits, 16 1-m^2 permanent plots and eight larger sectors of variable size (depending on the relief; approx. 50 m^2 and 150 m^2) are sampled	400-km^2 area subdivided with a 100 m × 100 m grid; of these grid points, 500 in grassland and 500 in forest vegetation are selected (not random); of these 1000 plots, 100 are intensive plots and 16 very intensive plots (the higher the "intensity", the more disciplines work together on one plot); various experimental approaches are included
Plot sizes for vascular plant monitoring	100 m^2, 1000 m^2, 10,000 m^2, (1 km^2)	Not standardized	Not standardized	1 m^2, approx. 100 m^2	16 m^2 in grassland, 400 m^2 in forest

Frequency and type of vegetation monitoring data	Annual to three-year monitoring of presence, cover and abundance of all vascular plant species	Not standardized	Species lists per observatory; vegetation not standardized	Irregular monitoring (every 5–10 years) of presence, cover and abundance of vascular plant, bryophyte, and lichen species on 1 m^2; rough 5-point scale cover-abundance estimate of vascular plants species in the 8 sectors	"Repeated" vegetation surveys, presence, abundance, cover estimates; intensive study sites: Standing biomass, growth, primary productivity
Number of subplots per site for vegetation monitoring	20 of each size (100 m^2, 1000 m^2, 10,000 m^2)	Not standardized	Not standardized, adapted to vegetation of the respective observatory	16 1-m^2 plots and 8 sectors per summit; at least 4 summits per site	100
Number of sites already implemented	46	523 (49 North America; 15 South America, 329 Europe, 12 Africa, 114 Asia, 4 Oceania)	12 pilot observatories, 25 in total	62 active (21 of these have been resurveyed), 15 in setup, 12 planned	3
Year of first implementation	2001	1980 (LTER in United , States) some of the sites now included in ILTER have been monitored for a even longer period	1992	2001	2006
Vegetation types covered	Desert, arid and humid savannas, forest-savanna mosaic, semi-deciduous tropical forest, fynbos	Any (boreal, temperate and tropical forests, tundras, prairie and other grassland ecosystems hot and cold deserts, wetlands, coastal ecosystems, lakes, coral reefs, ocean, agricultural and urban ecosystems)	Arid ecosystems around the Sahara	Alpine ecosystems (fromthe treeline ecotone upwards)	Grassland and forest ecosystems (from semi-natural to intensively used)
Regions covered	Africa (at present), but aiming at global application	Global, but sites are concentrated in industrialized countries	North Africa and Sahel	Global, but so far no site in Africa	Germany
Additional site information on potential drivers of biodiversity change	Automatic weather stations, land use type and intensity	Not standardized	Not standardized	Soil temperature (not in every site)	Weather station on 100 intensive plots per site: temperatures and humidity of soil and air
Website	www.biota-africa.org	www.ilternet.edu/	www.oss-online.org	www.gloria.ac.at	www.biodiversity-exploratories.de
Reference	The present paper	Kim (2006)	Aïdoud et al. (2008)	Pauli et al. (2004, 2009)	Fischer et al. (2010)

(*E*uropean *B*iodiversity *O*bservation *Ne*twork; see http://www.ebone.wur.nl/UK/) and ALTER-Net (*A* *L*ong-*T*erm Biodiversity, *E*cosystem and Awareness *R*esearch *Net*work; see http://www.alter-net.info) now aim at coordinating the various national monitoring initiatives.

The presently most comprehensive global biodiversity monitoring network, ILTER (Kim 2006; see Table 3), is actually a network of many independent national long-term observation networks lacking a functioning standardization in the monitoring protocol among the nations and often even within the national subnetworks. Therefore, ILTER, while comprising some of the most valuable ecological long-term datasets worldwide, is not comparable to the BIOTA Observatories that aim at generating standardized and thus globally comparable data for the future. The second global monitoring network, GLORIA, has a highly standardized, very detailed sampling protocol (Pauli et al. 2004, 2009), but is restricted to plants in one specific habitat type (mountain summits), with climate solely as a driving factor of biodiversity change (see Table 3). Two further supranational monitoring schemes, the European forest monitoring (Aamlid et al. 2007) and ROSELT/OSS (Aïdoud et al. 2008; see Table 3) are both restricted to specific ecosystems. Among the national biodiversity monitoring schemes, the Countryside Survey in the United Kingdom (CS; since 1978; e.g., Bunce 2000) and the Swiss BDM (since 2000; e.g., Hintermann et al. 2000) belong to the most extensive and methodologically most advanced programs. Within the BDM, for example, complete vascular plant species lists are recorded every 5 years for 1,600 10-m^2 permanent plots and for standardized transects within 520 1-km^2 areas alongside data on various animal groups (Hintermann et al. 2000). These plots are distributed in a stratified-random approach over the whole of Switzerland and thus allow the calculation of mean biodiversity trends across the territory of the country. Finally, the DFG Biodiversity Exploratories are outstanding among all reviewed monitoring schemes regarding the wide taxonomic coverage (including, apart from vascular plants and vertebrates, also bryophytes, lichens, many above- and below-ground invertebrates as well as fungi and microbes) and the inclusion of many experimental approaches. On the other hand, due to the lack of a completely random or systematic plot placement, they do not even allow derivation of spatially valid means of biodiversity parameters within each of the three Exploratories, let alone valid extrapolations to larger areas.

Regarding spatial scale, up to now, most monitoring schemes are restricted to only one scale, neglecting the fact that biodiversity patterns, their drivers and their responses to global change are likely to be scale-dependent (see Turner and Tjørve 2005; Field et al. 2009; Dengler 2009b). While the European forest monitoring suggests applying a uniform plot size of 400 m^2 (but in application among different countries plots of 10–1,200 m^2 are used; see Dengler 2009b), the German ÖFS and the DFG Biodiversity Exploratories, for example, use different plot sizes for individual habitat types. This makes comparison between studies impossible and does not allow for spatial or temporal transitions between habitat types. GLORIA and BDM both have two different spatial scales, but the bigger one (GLORIA: summit sector; BDM: transect within 1 km^2) is not comparable between sites. With presently three (or four if the 1 km^2 is also counted) defined spatial scales for sampling, the BIOTA Observatories are clearly outstanding in this respect. Only schemes like the Carolina Vegetation Survey (Peet et al. 1998) and the approach proposed by Dengler (2009b) analyze more spatial scales, but both have been applied only regionally for one-off inventories and not for monitoring so far.

Conclusions and outlook

The BIOTA Observatories provide the following basic features that have been identified as being critical for a design of a global biodiversity monitoring network: (a) they are standardized but at the same time flexible regarding the minimum number of hectare plots sampled; (b) they are designed for sampling at more than one spatial scale with down- and up-scaling options; (c) they focus on time series; (d) they are suitable interdisciplinary approaches; (e) they are applicable in all types of biomes; and (f) the highly flexible open-access database software BIOTABase facilitates the handling and processing of time-series data from nested plots as they are inherent to BIOTA Observatories. With this combination of features, BIOTA Observatories are unique among existing biodiversity monitoring schemes (see "Lessons learned and potential improvements"). The applicability of the BIOTA Observatory approach has been tested and proven for over 9 years of BIOTA research across a wide range of different biomes on the African continent. Many results from this standardized sampling on BIOTA Observatories in Africa have already been published, with many more analyses in progress, in particular, those of the 9-year monitoring data (see "Sampling of vascular plants").

The existing BIOTA Observatories provide important information on biodiversity patterns on different spatial scales—and therefore fill gaps of critical baseline information that are missing even for generally much better studied regions of the Earth than Africa. The long-term in situ monitoring, commenced on BIOTA Observatories and complemented by remote sensing, is critical to identify long-term trends in biodiversity changes and to differentiate them from medium-term responses of biodiversity to climatic oscillations (O'Connor and Roux 1995; Anyamba and Eastman 1996; Hereford et al. 2006). We thus propose considering the BIOTA Observatory design, potentially with those improvements suggested in "The BIOTA biodiversity observatories in Africa", for worldwide application. This approach is applicable in any terrestrial (and semi-terrestrial) biome and landscape worldwide, irrespective of spatio-temporal heterogeneity or degree of human influence, and provides a wide array of standardized indicators of biodiversity, its change and its driving factors in a time- and cost-efficient manner.

The BIOTA Observatories in Africa have been implemented and monitored by a team of African and German researchers. Based on our experiences, we promote the continuation and extension of the monitoring on BIOTA Observatories in Africa and the extension of this initiative into other parts of the world. The discussed strengths of the BIOTA Observatory design suggest them as a key component of the Biodiversity Observation Network (GEO BON) within the Global Earth Observation System of Systems (GEOSS; Scholes et al. 2008). Such a global network of standardized BIOTA Observatories that provide empirical, spatially explicit information on biodiversity and, more general, environmental changes, would be a crucial contribution for global change research in order to develop adaptation and mitigation strategies from local to global scales.

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Field(s)	**Notes**
Latitude (°)	WGS84; north-west corner of BIOTA Observatory
Longitude (°)	WGS84; north-west corner of BIOTA Observatory
Mean annual temperature (°C)	Modelled data for 1950-2000; WorldClim Bioclim dataset BIO1; Source: Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climat. 25, 1965-1978.
Mean annual precipitation (mm)	Modelled data for 1950-2000; WorldClim Bioclim dataset BIO12; Source: Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climat. 25, 1965-1978.
Biome	Classification within BIOTA AFRICA
WWF ecoregion	Source: Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'Amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P., Kassem, K.R., 2001. Terrestrial ecoregions of the World: a new map of life on Earth. BioScience 51, 933–938.
Intensity of land use	Landuse intensity classe (none = no grazing or other land use; low = e.g. low-intensity grazing by game in a nature reserve; medium = sustainable land use; high = degrading land use)
Years with vascular plant data	x = data available in BIOTABase; (x) = data in process (will be available soon)

Observatory No.	Observatory name	Country	Primary administrative unit	Secondary administrative unit	Locality	Farm name and number	Latitude (°)	Longitude (°)	Altitude (m a.s.l.)	Mean annual temperature (°C)	Mean annual precipitation (mm)
BIOTA Maroc											
M01	El Miyit	Morocco	Souss-Massa-Draâ	Zagora	Tizi n Tafilalet	-	30.36741	-5.63236	1869	22.5	57
M02	Taoujgalt	Morocco	Souss-Massa-Draâ	Ouarzazate	Taoujgalt	-	31.38864	-6.32585	736	21.6	298
BIOTA West Africa											
W01	Yomboli	Burkina Faso	Sahel	Oudalan	Yomboli	-	14.61480	-0.38129	286	29.0	364
W02	Kolel	Burkina Faso	Sahel	Oudalan	Kolel	-	14.54518	-0.38439	295	29.0	374
W03	Kikideni	Burkina Faso	Est	Gourma	Kikideni	-	11.87341	0.37442	304	27.9	842
W04	Natiabouani	Burkina Faso	Est	Gourma	Natiabouani	-	11.64648	0.51929	258	28.2	855
W05	Alibori	Benin	Atacora	Péhunco	Péhunco	-	10.41762	2.24676	297	27.0	1085
W06	Terroire Villageois	Benin	Atacora	Péhunco	Péhunco	-	10.14469	2.24961	327	26.4	1121
W07	Comoé	Ivory Coast	Zanzan	Bouna	Parc National de la Comoé	-	8.76667	-3.83333	220	27.0	1050
BIOTA Southern Africa: North-South Transect, Namibia											
S01	Mile 46	Namibia	Kavango	Rundu	near Cove	Alex Morenga Livestock Development Centre	-18.30183	19.24731	1180	22.2	536
S02	Mutompo	Namibia	Kavango	Rundu	near Cove	Mutompo	-18.30178	19.25833	1180	22.2	536
S03	Sonop	Namibia	Otjozondjupa	Grootfontein	near Maroelaboom	Sonop 903	-19.07382	18.90390	1236	21.8	497
S04	Toggekry	Namibia	Otjozondjupa	Okahandja	Omatako	Omatako Ranch 305	-21.50144	16.72933	1519	19.2	394
S05	Otjiamongombe	Namibia	Otjozondjupa	Okahandja	Erichsfelde	Otjiamongombe West 44	-21.59683	16.93511	1495	19.4	396
S06	Okamboro	Namibia	Otjozondjupa	Okahandja	Ovitoto	Okamboro Ovitoto 55	-22.01918	17.06248	1490	19.7	398
S08	Niko North	Namibia	Hardap	Mariental	near Gibeon	Niko 377 grazing	-25.34251	17.83909	1070	19.5	238
S09	Niko South	Namibia	Hardap	Mariental	near Gibeon	Niko 377 reserve	-25.33341	17.84897	1076	19.5	238
S10	Gellap Ost	Namibia	Karas	Keetmanshoop	Keetmanshoop	Gellap Ost 3	-26.40120	18.00484	1099	20.6	153
S11	Nabaos	Namibia	Karas	Keetmanshoop	Keetmanshoop	Nabaos 7	-26.39064	17.99548	1045	20.8	146
S12	Karios	Namibia	Karas	Karas	Karasburg	Karios - Fish River Canyon	-27.67652	17.80396	909	19.1	98
S16	Wlotzkasbaken	Namibia	Erongo	Arandis	Swakopmund	Wlotzkasbaken - Mile 14	-22.31500	14.45948	73	16.9	12
S42	Ogongo	Namibia	Omusati	Uutapi	Ogongo	Ogongo Agricultural College	-17.69720	15.30521	1103	22.7	469
S43	Omano go Njamba	Namibia	Omusati	Uutapi	Ogongo	Omano go Njamba	-17.70803	15.26480	1100	22.7	467
BIOTA Southern Africa: North-South Transect, South Africa											
S17	Alpha	South Africa	Northern Cape	Siyanda	Askham	Alpha	-26.76092	20.61402	896	20.1	185
S18	Koeroegap Vlakte	South Africa	Northern Cape	Namakwa	Sendelingsdrif	Koeroegap Vlakte	-28.22665	17.02567	635	17.0	73
S20	Numees	South Africa	Northern Cape	Namakwa	Sendelingsdrif	Numees	-28.29309	16.95381	362	17.6	57
S21	Groot Derm	South Africa	Northern Cape	Namakwa	Alexander Bay	Groot Derm - Yellow Dune	-28.61234	16.65433	193	17.6	57
S22	Soebatsfontein	South Africa	Northern Cape	Namakwa	Soebatsfontein	Soebatsfontein Commonage	-30.18650	17.54337	392	17.0	146
S24	Paulshoek	South Africa	Northern Cape	Namakwa	Leliefontein	Leliefontein 624 (Paulshoek)	-30.38568	18.27579	1048	15.3	252
S25	Remhoogte	South Africa	Northern Cape	Namakwa	Leliefontein	Remhoogte 416 (Rooiwal)	-30.39536	18.27570	1027	15.5	247
S26	Goedehoop	South Africa	Western Cape	West Coast	Van Rhynsdorp	Flaminkvalkte 111 (Goedehoop)	-31.27671	18.59152	245	19.0	162
S27	Ratelgat	South Africa	Western Cape	West Coast	Van Rhynsdorp	Luiperskop 211 (Ratelgat)	-31.28588	18.60031	239	19.1	159
S28	Moedverloren	South Africa	Western Cape	West Coast	Vredendal	Moedverloren 208	-31.46093	18.43906	140	18.7	162
S29	Rocherpan	South Africa	Western Cape	West Coast	Piquetberg	Rocherpan Nature Reserve	-32.60085	18.30560	35	17.6	251
S31	Riverlands	South Africa	Western Cape	West Coast	Malmesbury	Riverlands	-33.48934	18.58012	140	16.8	453
S32	Elandsberg	South Africa	Western Cape	Cape Winelands	Wellington	Elandsberg	33.41416	19.03111	95	18.0	560
S33	Cape of Good Hope	South Africa	Western Cape	City of Cape Town	Table Mountain National Park	Cape of Good Hope - Cape Peninsula	-34.26020	18.39229	83	16.3	689
S45	Nieuwoudtville	South Africa	Northern Cape	Namakwa	Nieuwoudtville	Glenlyon	-31.39002	19.12880	722	16.3	301
BIOTA Southern Africa: East-West Transect, Namibia											
S34	Kleinberg	Namibia	Erongo	Walfis Bay	Walfis Bay	Kleinberg	-22.98984	14.72518	188	17.6	16
S35	Gobabeb	Namibia	Erongo	Swakopmund	Gobabeb	Gobabeb	-23.53241	15.04689	419	21.0	21
S36	Ganab	Namibia	Erongo	Swakopmund	Namib-Naukluft Park	Ganab	-23.12182	15.53844	995	19.5	129
S37	Rooisand	Namibia	Khomas	Windhoek	Rooisand Desert Ranch	Chausib 27	-23.29454	16.10498	1160	19.5	200
S38	Claratal	Namibia	Khomas	Windhoek	Windhoek	Claratal 18	-22.77938	16.77485	1865	18.0	335
S39	Narais	Namibia	Khomas	Windhoek	near Rehoboth	Narais	-23.12038	16.89658	1624	18.6	289
S40	Duruchaus	Namibia	Khomas	Windhoek	near Rehoboth	Duruchaus	-23.13318	16.90000	1614	18.6	287
S41	Sandveld	Namibia	Omaheke	Gobabis	near Drimiopsis	Dipcadi 389	-22.04335	19.13390	1523	19.1	397

Observatory No.	Observatory name	Biome	WWF ecoregion	Tenure	Intensity of land use	Type and history of land use	Soil data
BIOTA Maroc							
M01	El Miyit	Saharan Semidesert	PA1321 – North Saharan steppe and woodlands	collective	high	rangeland for dromedaries and goats	-
M02	Taoujgalt	Ibero-Mauritanian Sagebrush Steppe	PA1214 – Mediterranean woodlands and forests	collective	high	rangeland for sheep, goats and dromedaries	-
BIOTA West Africa							
W01	Yomboli	Sahel Grass- and Shrubland	AT0722 – West Sudanian savanna	communal	medium	pasture	-
W02	Kolel	Sahel Grass- and Shrubland	AT0722 – West Sudanian savanna	communal	medium	pasture	-
W03	Kikideni	North Sudanian Savanna	AT0722 – West Sudanian savanna	communal	medium	pasture	x
W04	Natiabouani	North Sudanian Savanna	AT0722 – West Sudanian savanna	state	medium	protected	x
W05	Alibori	South Sudanian Savanna	AT0713 – Sahelian Acacia savanna	state	medium	protected	x
W06	Terroire Villageois	South Sudanian Savanna	AT0722 – West Sudanian savanna	communal	medium	pasture	x
W07	Comoé	South Sudanian Savanna	AT0713 – Sahelian Acacia savanna	state	low	protected since 1926, annual savanna burning and poaching	-
BIOTA Southern Africa: N							
S01	Mile 46	Southern African Woodland Savanna	AT0726 – Zambezian Baikiaea woodlands	state	high	breeding experiments and standard rotational grazing, farming with goats and cattle	x
S02	Mutompo	Southern African Woodland Savanna	AT0726 – Zambezian Baikiaea woodlands	communal	medium	farming with cattle	x
S03	Sonop	Southern African Woodland Savanna	AT0709 – Kalahari Acacia-Baikiaea woodlands	state	medium	experimental farming with cattle, game	x
S04	Toggekry	Southern African Thornbush Savanna	AT1309 – Kalahari xeric savanna	private	medium	farming with game for hunting, cattle farming	x
S05	Otjiamongombe	Southern African Thornbush Savanna	AT1309 – Kalahari xeric savanna	private	medium	farming with cattle and game for hunting	x
S06	Okamboro	Southern African Thornbush Savanna	AT1309 – Kalahari xeric savanna	communal	high	farming with cattle, goats and sheep	x
S08	Niko North	Nama Karoo	AT1316 – Namibian savanna woodlands	communal	medium	rotational farming with goats	-
S09	Niko South	Nama Karoo	AT1316 – Namibian savanna woodlands	communal	medium	rotational farming with goats	-
S10	Gellap Ost	Nama Karoo	AT1316 – Namibian savanna woodlands	state	medium	experimental farming and breeding with sheep and goats	x
S11	Nabaos	Nama Karoo	AT1316 – Namibian savanna woodlands	communal	high	farming with goats and sheep	x
S12	Karios	Nama Karoo	AT1314 – Nama Karoo	private	low	farming with springbok and oryx	x
S16	Wlotzkasbaken	Namib Desert	AT1315 – Namib desert	state	none	recreatation area	x
S42	Ogongo	Southern African Woodland Savanna	AT0702 – Angolan Mopane woodlands	state	low	Demonstration farming with cattle	x
S43	Omano go Njamba	Southern African Woodland Savanna	AT0702 – Angolan Mopane woodlands	state	high	farming with cattle and smallstock	x
BIOTA Southern Africa: N							
S17	Alpha	Southern African Thornbush Savanna	AT1309 – Kalahari xeric savanna	private	medium	nature reserve, game farming	x
S18	Koeroegap Vlakte	Succulent Karoo	AT1322 – Succulent Karoo	communal	medium	farming with cattle, sheep and goats	x
S20	Numees	Succulent Karoo	AT1322 – Succulent Karoo	communal	medium	farming with cattle, sheep and goats	x
S21	Groot Derm	Succulent Karoo	AT1322 – Succulent Karoo	private	low	nature reserve	x
S22	Soebatsfontein	Succulent Karoo	AT1322 – Succulent Karoo	communal	medium	farming with sheep and goats	x
S24	Paulshoek	Succulent Karoo	AT1322 – Succulent Karoo	communal	high	farming with goats and sheep	x
S25	Remhoogte	Succulent Karoo	AT1322 – Succulent Karoo	private	low	farming with sheep, few horses	x
S26	Goedehoop	Succulent Karoo	AT1322 – Succulent Karoo	private	medium	farming with sheep	x
S27	Ratelgat	Succulent Karoo	AT1322 – Succulent Karoo	communal	medium	farming with sheep	x
S28	Moedverloren	Succulent Karoo	AT1322 – Succulent Karoo	state	low	nature reserve	-
S29	Rocherpan	Fynbos	AT1202 – Lowland fynbos and renosterveld	state	none	nature reserve	-
S31	Riverlands	Fynbos	AT1202 – Lowland fynbos and renosterveld	state	none	nature reserve	-
S32	Elandsberg	Fynbos	AT1202 – Lowland fynbos and renosterveld	private	none	nature reserve	x
S33	Cape of Good Hope	Fynbos	AT1203 – Montane fynbos and renosterveld	state	none	nature reserve	x
S45	Nieuwoudtville	Fynbos	AT1322 – Succulent Karoo	state	none	nature reserve	-
BIOTA Southern Africa: Ea							
S34	Kleinberg	Namib Desert	AT1315 – Namib desert	state	none	nature reserve	-
S35	Gobabeb	Namib Desert	AT1315 – Namib desert	state	none	nature reserve	-
S36	Ganab	Namib Desert	AT1316 – Namibian savanna woodlands	state	none	nature reserve	-
S37	Rooisand	Southern African Thornbush Savanna	AT1316 – Namibian savanna woodlands	private	medium	Cattle farming and tourism	-
S38	Claratal	Southern African Thornbush Savanna	AT1309 – Kalahari xeric savanna	private	medium	Farming with cattle and game	x
S39	Narais	Nama Karoo	AT1309 – Kalahari xeric savanna	private	low	farming with cattle and goats, some game	x
S40	Duruchaus	Nama Karoo	AT1309 – Kalahari xeric savanna	private	medium	farming with cattle, sheep and goats	x
S41	Sandveld	Southern African Thornbush Savanna	AT1309 – Kalahari xeric savanna	state	medium	Experimental farming with cattle	x

				Years with vascular plant data										
Observatory No.	Observatory name	Deviations from standard soil sampling	Years with vascular plant data	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Deviations from standard vascular plant sampling
BIOTA Maroc														
M01	El Miyit	only explorative soil profiles	2002, 2003, 2005-2009	-	x	x	-	x	x	x	x	x	-	ranks 1-40; without 1000 m²
M02	Taoujgalt	only explorative soil profiles	2002-2005, 2008, 2009	-	x	x	x	x	-	-	x	x	-	ranks 1-40; without 1000 m²
BIOTA West Africa				-	-	-	-	-	-	-	-	-	-	
W01	Yomboli		2001, 2002	x	x	-	-	-	-	-	-	-	-	ranks 1-10
W02	Kolel		2001	x	-	-	-	-	-	-	-	-	-	ranks 1-10
W03	Kikideni	with different sampling design	2001, 2003	x	-	x	-	-	-	-	-	-	-	ranks 1-10
W04	Natiabouani	with different sampling design	2001-2003	x	x	x	-	-	-	-	-	-	-	ranks 1-10
W05	Alibori	with different sampling design	2002	-	x	-	-	-	-	-	-	-	-	ranks 1-10
W06	Terroire Villageois	with different sampling design	2002	-	x	-	-	-	-	-	-	-	-	ranks 1-10
W07	Comoé		2001	x	-	-	-	-	-	-	-	-	-	ranks 1-15
BIOTA Southern Africa: No														
S01	Mile 46	only ranks 1-15, plus transect (ranks 19, 24, 25, 32, 76, 79, 88, 90)	2001-2003, 2005-2009	x	x	x	-	x	x	x	x	x	-	
S02	Mutompo	only ranks 1-15, plus transect (ranks 20, 22, 31, 90)	2001-2003, 2005-2009	x	x	x	-	x	x	x	x	x	-	
S03	Sonop	plus transect (ranks 51, 55, 57, 59, 61)	2001-2003, 2005, 2006, 2008, 2009	x	x	x	-	x	x	-	x	x	-	
S04	Toggekry	plus ranks 26-40, 70	2001-2009	x	x	x	x	x	x	x	x	x	-	
S05	Otjiamongombe	plus ranks 39	2004-2009	-	-	-	x	x	x	x	x	x	-	
S06	Okamboro	plus ranks 30, 50	2004-2009	-	-	-	x	x	x	x	x	x	-	
S08	Niko North		2001, 2002, 2004, 2006-2009	x	x	-	x	-	x	x	x	x	-	
S09	Niko South		2001, 2002, 2004, 2006-2009	x	x	-	x	-	x	x	x	x	-	
S10	Gellap Ost		2001-2009	x	x	x	x	x	x	x	x	x	-	
S11	Nabaos	plus ranks 26, 68, 69	2001-2009	x	x	x	x	x	x	x	x	x	-	
S12	Karios	soil samples are from the non-established BIOTA Observatory S13 nearby	2001-2009	x	x	x	x	x	x	x	(x)	x	-	
S16	Wlotzkasbaken		2001-2003, 2005, 2010	x	x	x	-	x	-	-	-	-	(x)	
S42	Ogongo	only ranks 1-24	2007-2009	-	-	-	-	-	-	x	x	x	-	
S43	Omano go Njamba		2007-2009	-	-	-	-	-	-	x	x	x	-	
BIOTA Southern Africa: No														
S17	Alpha		2002, 2003, 2005-2007	-	x	x	-	x	x	x	-	-	-	
S18	Koeroegap Vlakte		2001-2009	x	x	x	x	x	x	x	(x)	(x)	-	
S20	Numees	plus rank 65	2001-2003, 2006	x	x	x	-	-	x	-	-	-	-	
S21	Groot Derm	only ranks 1-15	2001-2006, 2008	x	x	x	x	x	x	-	x	-	-	
S22	Soebatsfontein	plus ranks 27, 29	2001-2009	x	x	x	x	x	x	x	x	x	-	
S24	Paulshoek		2001-2009	x	x	x	x	x	x	x	x	x	-	
S25	Remhoogte		2001-2009	x	x	x	x	x	x	x	x	x	-	
S26	Goedehoop		2001-2009	x	x	x	x	x	x	x	x	x	-	ranks 1-9, 30
S27	Ratelgat		2001-2009	x	x	x	x	x	x	x	x	x	-	ranks 1-10
S28	Moedverloren		2001-2009	x	x	x	x	x	x	x	x	x	-	
S29	Rocherpan		2005	-	-	-	-	x	-	-	-	-	-	
S31	Riverlands		2004, 2008, 2009	-	-	-	x	-	-	-	x	x	-	
S32	Elandsberg		2009	-	-	-	-	-	-	-	-	x	-	
S33	Cape of Good Hope		2008, 2009	-	-	-	-	-	-	-	x	x	-	
S45	Nieuwoudtville		2007	-	-	-	-	-	-	(x)	-	-	-	ranks 1, 2, 5, 8 on 100 m2
BIOTA Southern Africa: Ea														
S34	Kleinberg		2010	-	-	-	-	-	-	-	-	-	x	ranks 1-100, only 10,000 m²
S35	Gobabeb		2004	-	-	-	x	-	-	-	-	-	-	
S36	Ganab		2010	-	-	-	-	-	-	-	-	-	(x)	
S37	Rooisand		2005	-	-	-	-	x	-	-	-	-	-	
S38	Claratal		2005, 2007, 2009	-	-	-	-	x	-	x	-	x	-	
S39	Narais		2004-2009	-	-	-	x	x	x	x	x	x	-	
S40	Duruchaus		2004-2009	-	-	-	x	x	x	x	x	x	-	
S41	Sandveld		2005, 2008, 2009	-	-	-	-	x	-	-	x	x	-	