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PERSPECTIVES

Implementing large-scale and long-term functional biodiversity research: The Biodiversity Exploratories

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Abstract

Functional biodiversity research explores drivers and functional consequences of biodiversity changes. Land use change is a major driver of changes of biodiversity and of biogeochemical and biological ecosystem processes and services. However, land use effects on genetic and species diversity are well documented only for a few taxa and trophic networks. We hardly know how different components of biodiversity and their responses to land use change are interrelated and very little about the simultaneous, and interacting, effects of land use on multiple ecosystem processes and services. Moreover, we do not know to what extent land use effects on ecosystem processes and services are mediated by biodiversity change. Thus, overall goals are on the one hand to understand the effects of land use on biodiversity, and on the other to understand the modifying role of biodiversity change for land-use effects on ecosystem processes, including biogeochemical cycles. To comprehensively address these important questions, we recently established a new large-scale and long-term project for functional biodiversity, the Biodiversity Exploratories (www.biodiversity-exploratories.de). They comprise a hierarchical set of standardized field plots in three different regions of Germany covering manifold management types and intensities in grasslands and forests. They serve as a joint research platform for currently 40 projects involving over 300 people studying various aspects of the relationships between land use, biodiversity and ecosystem processes through monitoring, comparative observation and experiments. We introduce guiding questions, concept and design of the Biodiversity Exploratories – including main aspects of selection and implementation of field plots and project structure – and we discuss the significance of this approach for further functional biodiversity research. This includes the crucial relevance of a common study design encompassing variation in both drivers

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and outcomes of biodiversity change and ecosystem processes, the interdisciplinary integration of biodiversity and ecosystem researchers, the training of a new generation of integrative biodiversity researchers, and the stimulation of functional biodiversity research in real landscape contexts, in Germany and elsewhere.

Zusammenfassung

Funktionelle Biodiversitätsforschung erforscht die Ursachen und funktionellen Konsequenzen von Biodiversitätsveränderungen. Landnutzung gehört zu den wichtigsten Ursachen von Änderungen von Biodiversität und biogeochemischen und biologischen Ökosystemprozessen und -leistungen. Allerdings sind Landnutzungsauswirkungen auf genetische und Artendiversität bisher nur für wenige Taxa und trophische Netzwerke gut dokumentiert. Zudem ist kaum bekannt, wie verschiedene Komponenten der Biodiversität und ihre Reaktion auf Landnutzungsänderungen zusammenhängen. Auch ist wenig über gleichzeitige und miteinander wechselwirkende Effekte der Landnutzung auf mehrere verschiedene Ökosystemprozesse und -leistungen bekannt. So ist auch noch unklar, inwieweit Landnutzungseffekte auf Ökosystemprozesse und -leistungen durch Biodiversitätsveränderungen vermittelt werden. Es gilt also einerseits Landnutzungseffekte auf Biodiversität zu verstehen und andererseits die modifizierende Rolle von Biodiversitätsveränderungen für Landnutzungseffekte auf Ökosystemprozesse, einschliesslich biogeochemischer Kreisläufe. Um diese wichtigen Fragen umfassend zu untersuchen, haben wir kürzlich ein grosses und langfristiges Projekt zur funktionellen Biodiversitätsforschung gestartet, die Biodiversitäts-Exploratorien (www.biodiversity-exploratories.de). Diese umfassen einen Satz standardisierter Untersuchungsflächen in drei Regionen Deutschlands, die jeweils vielfältige Typen und Intensitäten der Wald- und Grünlandnutzung umfassen. Sie dienen als gemeinsame Forschungsplattform für gegenwärtig 40 Projekte mit über 300 Beteiligten, die verschiedenste Aspekte der Beziehung zwischen Landnutzung, Biodiversität und Ökosystemprozessen durch Monitoring, vergleichende Beobachtung und Experimente untersuchen. Wir stellen Leitfragen, Konzept und Design der Biodiversitätsexploratorien vor – einschliesslich der wesentlichen Aspekte der Auswahl und Einrichtung der Untersuchungsflächen und der Projektstruktur – und wir diskutieren die Bedeutung des Ansatzes für die weitere funktionelle Biodiversitätsforschung. Diese beinhaltet die zentrale Bedeutung des gemeinsamen Forschungsdesigns, das sowohl Ursachen als auch Konsequenzen der Veränderungen von Biodiversität und Ökosystemprozessen umfasst, die interdisziplinäre Integration von Biodiversitäts- und Ökosystemforschenden, die Ausbildung einer neuen Generation von integrativen Biodiversitätsforschern und die Anregung funktioneller Biodiversitätsforschung im realen Landschaftskontext, in Deutschland und darüber hinaus.

Keywords: Biotic interactions; Ecological monitoring; Ecosystem services; Forest management; Grassland; Land use; Landscape; Species richness

Introduction

Functional biodiversity research explores drivers and functional consequences of biodiversity changes. Biodiversity comprises all scales of biological organization, spanning intra-specific genetic, morphological and demographic diversity, species and community diversity, the diversity of biological interactions between organisms and the diversity of ecosystems in the landscape (Wilson 2001). Environmental effects on species diversity and genetic diversity are well established only for few taxa, and no project in the world is currently addressing all facets of biodiversity in a single framework. Accordingly, we hardly know how different elements of biodiversity are interrelated (Lamoreux et al. 2006; Wolters, Bengtsson, & Zaitsev 2006). This is exemplified by the very scarcely studied relationship between species diversity and genetic diversity within species (Van Valen 1965; Vellend 2005; Vellend & Geber 2005), where current knowledge is limited to a few case studies relating community species diversity to molecular genetic diversity of single species. Another example is soil biodiversity, where, despite pioneering large-scale programs such as the UK soil biodiversity project (http://soilbio.nerc.ac.uk/), very little is still known about the relationship between plant diversity and the diversity of soil invertebrates, fungi and microbes (Wardle et al. 2004; van der Heijden, Bardgett, & van Straalen 2008).

The relevance of land use change in functional biodiversity research

Among the major drivers of current changes of biodiversity and of ecosystem processes and services, land use change is the most prominent (Sala et al. 2000) ranging from local and regional (Hietel, Waldhardt, & Otte 2005) to national (Stöcklin, Bosshard, Klaus, Rudmann-Maurer, & Fischer 2007), international and global scales (Houghton 1994). In Germany, forests and grasslands are, along with croplands, among the most important ecosystems affected by human requirements. The natural vegetation cover of Germany mainly consisting of deciduous forests has been largely replaced by production forests, e.g. spruce plantations, and is now restricted to rather small and highly fragmented areas (Ellenberg 1996; MCPFE 2007). Furthermore, nutrient-poor grasslands, formerly only used at low intensities by humans and forming the most species-rich assemblages, are now either threatened by abandonment or by land-use intensification (Poschlod, Bakker, & Kahmen 2005; Maskell, Smart, Bullock, Thompson, & Stevens 2010). The Biodiversity Exploratories described below focus on forest and grassland habitats ranging from unmanaged forest and hardly used grassland to intensively used forest and grassland.

Currently, biodiversity experiences a general decline, in Central Europe especially at the local and regional scales (Settele et al. 2010). In terrestrial habitats, this is mainly due to habitat loss and ongoing changes in land use. In forests this is furthered by indirect effects of browsing ruminants, and enhanced by the displacement of native by alien species, by industrial emissions of nitrogen, organic compounds and heavy metals, and by climate change (Sala et al. 2000; Millenium Ecosystem Assessment 2005; Thuiller 2007). Although the mostly negative relationship between biodiversity and current land-use intensification is rather well known for some taxa, in particular vertebrates, vascular plants and some invertebrates such as grasshoppers or butterflies, it is not known for many others. The most obvious ecological mechanisms contributing to declining grassland biodiversity after land use change are competitive exclusion due to increased productivity (Grime 1973; Mittelbach et al. 2001) and species loss due to increased disturbance (Grime 1973; Biswas & Mallik 2010). However, as most case studies quite coarsely compare fertilized with unfertilized or more with less disturbed sites, differentiated statements on the amount and mechanism of biodiversity change after land use change are scarce. For instance, disturbance by grazing may enhance plant diversity on fertile grasslands and decrease it on less fertile grasslands (Proulx & Mazumder 1998). Last but not least, predicting the consequences of land use change for biodiversity change involves disentangling direct effects of land use on the diversity of higher trophic levels from indirect effects mediated by changes in plant diversity (Cardinale et al. 2006; Grace et al. 2007).

In principle, similar considerations as for grasslands also apply to forest trees and understory plants. Of course, effects of forest management additionally depend on number and identity of planted tree species (Hunter 1999). Moreover, the effect of age-class forests can only be studied by comparing several successional stages with unmanaged forests, which are characterised by more continuous tree age distribution. Of particular additional importance in Central European forests is the pressure of large herbivores such as deer and wild boar (MCPFE 2007; Ammer 2009).

Ecosystem processes and services

Society is interested in proper and continuous functioning of ecosystem processes and services. These include the pools and fluxes of water, carbon and nutrients, the maintenance of soil fertility, clean water and air, the provisioning of food and construction material, pollination and pest control (Daily 1997). The biodiversity-ecosystem functioning relationship is a rapidly expanding research area in ecology and evolution (Hooper et al. 2005). To date, a number of model experiments have addressed the functional consequences of changes of plant species composition and diversity (Hector et al. 1999; Tilman et al. 2001; Roscher et al. 2005). While overall effects of plant species composition, such as presence or absence of legumes or grasses, on biogeochemical cycles and other ecosystem processes are widely acknowledged (Spehn et al. 2002), very little is known about the role of individual species. It has been shown repeatedly that ecosystem processes and services depend not only on the species composition of ecosystems but also, and mostly positively, on their species richness (e.g., Naeem, Thompson, Lawler, Lawton, & Woodfin 1994; Hooper et al. 2005; Balvanera et al. 2006). Moreover, higher plant species diversity matters for the simultaneous maintenance of multiple ecosystem processes (Hector & Bagchi 2007).

In the real-world landscape context, positive correlations between biodiversity and ecosystem processes have been reported for some taxa (Hooper et al. 2005; Balvanera et al. 2006). Moreover, restoration projects aiming at enhanced biodiversity were reported to also enhance ecosystem services (Benayas, Newton, Diaz, & Bullock 2009). First experiments manipulating plant species diversity at several sites indicate positive relationships of plant species diversity and production (e.g. Stein, Auge, Fischer, Weisser, & Prati 2008). However, replicated experiments manipulating the biodiversity also of other taxa at many sites in real landscapes are missing completely. Overall, the relevance of positive biodiversity-ecosystem functioning relationships established in model experiments for real-world ecosystems is far from being well established.

Research approaches on drivers and consequences of biodiversity change

Understanding the interactions between land use, biodiversity, and ecosystem functioning requires long-term observational, comparative and experimental studies at an appropriate spatial scale (Fischer et al. 2010). While short-term laboratory and small field-experiments are useful tools to test particular hypotheses, such experiments are insufficient to understand processes at the ecosystem level in nature (Carpenter 1996; Symstad et al. 2003). Most experiments on the biodiversity-ecosystem functioning relationship have been conducted in the laboratory or on small field plots (Hooper et al. 2005). Thus, we need to conduct experiments in the field, at a scale large enough to represent natural biogeochemical cycles. Moreover, because different regions differ in their landscapes, resources, conditions, species pools, and socio-economic settings, studies need to be performed in several regions (Beck 2004). This is absolutely fundamental, because otherwise results cannot be generalised. Finally, to separate trends from fluctuations, to improve intra- and extrapolation of available observations, to test ecological models, and to allow parameterising models for predicting change under future scenarios, functional biodiversity research needs to cover long periods of time.

Working in several real landscapes creates multiple challenges for data analysis and interpretation. The drivers of biodiversity, such as land use and soil conditions, are rarely completely independent or perfectly balanced, as it is desirable in a planned experiment. Spatial auto-correlation in a plot-based sampling design needs to be taken into account in some organisms, but not in others, depending on their mobility. Moreover, research plots need to be large enough for experiments not to influence each other, but still spatially homogeneous enough to allow the integration of different results from the same plot. Finally, the work load to assess biodiversity and to run experiments varies considerably between taxa and this requires some flexibility of the design in terms of temporal and spatial replication. Thus, a fundamental goal of any large-scale, interdisciplinary project is to integrate the diverging demands of individual disciplines and to foster their optimal cooperation.

The Biodiversity Exploratories

To comprehensively address important questions on the feedback between land use, biodiversity and ecosystem processes in real-world ecosystems we recently established a new large-scale and long-term project for functional biodiversity research, the Biodiversity Exploratories (www.biodiversity-exploratories.de). We use the term “Exploratories” to emphasize that the project is not only based on observation and between-plot comparison, which could have been described by the term “observatories”, but that the project very importantly also involves replicated field experimentation in order to gain causal insights.

Here we illustrate the key requirements for successful implementation of a comprehensive land use-biodiversity-ecosystem process project by describing the main features of the Biodiversity Exloratories. We emphasize the importance of the common study design with many replicate plots for interdisciplinary research, for addressing overarching questions, and for quantitative synthesis of research results. We conclude by highlighting the role and significance of the Biodiversity Exploratories in relation to other initiatives, and we draw conclusions for future research.

Design of the Biodiversity Exploratories

Main rationale of design

A key aspect of the Biodiversity Exploratories is the system of standardized study plots, which are jointly used by all involved research groups. Such a common study design is pivotal for statistical comparisons across taxa, land use types, or geographical regions, and a lack thereof has hampered many cooperative projects in the past.

To allow for the test of consistency and generality of land-use effects across geographic regions, the Biodiversity Exploratories were established in three different regions of Germany (see Table 1, Fig. 1). Within each region, we established a network of field plots in grasslands and forests of different land use types and intensities. All plots within one region are collectively termed an “exploratory”. Within each exploratory, there are three hierarchical levels of study plots, on which research of different intensity and detail is conducted (Tables 2 and 3): (1) about 1000 grid plots (GPs), 500 in grasslands and 500 in forests, which are mainly used for large-scale analyses of biodiversity data and their relationships to land use and other environmental factors, (2) 100 experimental plots (EPs), 50 in grasslands and 50 in forests, which are a selected subset of the respective grid plots serving as a platform for more thorough biodiversity assessment and environmental monitoring, as well as for several manipulative experiments, and (3) 18 very intensive plots (VIPs), half in grasslands and half in forests, which are a subset of the experimental plots used for studying biodiversity or ecological processes in extreme detail or requiring very labour-intensive methods, for which the use of the experimental plots is not feasible. In one of the exploratories (Hainich-Dün), where selection forests are an especially important forest type, we established three further very intensive plots in these forests. Altogether, the Biodiversity Exploratories comprise 57 very intensive plots, 300 experimental plots, and some 3000 grid plots. Below, we describe the rationale and selection of each of these plot types in more detail.

Table 1. Main geographic and environmental characteristics of the three Biodiversity Exploratories.

	Schorfheide-Chorin	Hainich-Dün	Schwäbische Alb
Location	NE Germany	Central Germany	SW Germany
Size	$\sim 1300\,km^2$	$\sim 1300\,km^2$	$\sim 422\,km^2$
Geology	Young glacial landscape	Calcareous bedrock	Calcareous bedrock with karst phenomena
Human population density	$23\,km^{-1}$	$116\,km^{-1}$	$258\,km^{-1}$
Altitude a.s.l.	3–140 m	285–550 m	460–860 m
Annual mean temperature	8–8.5 °C	6.5–8 °C	6–7 °C
Annual mean precipitation	500–600 mm	500–800 mm	700–1000 mm

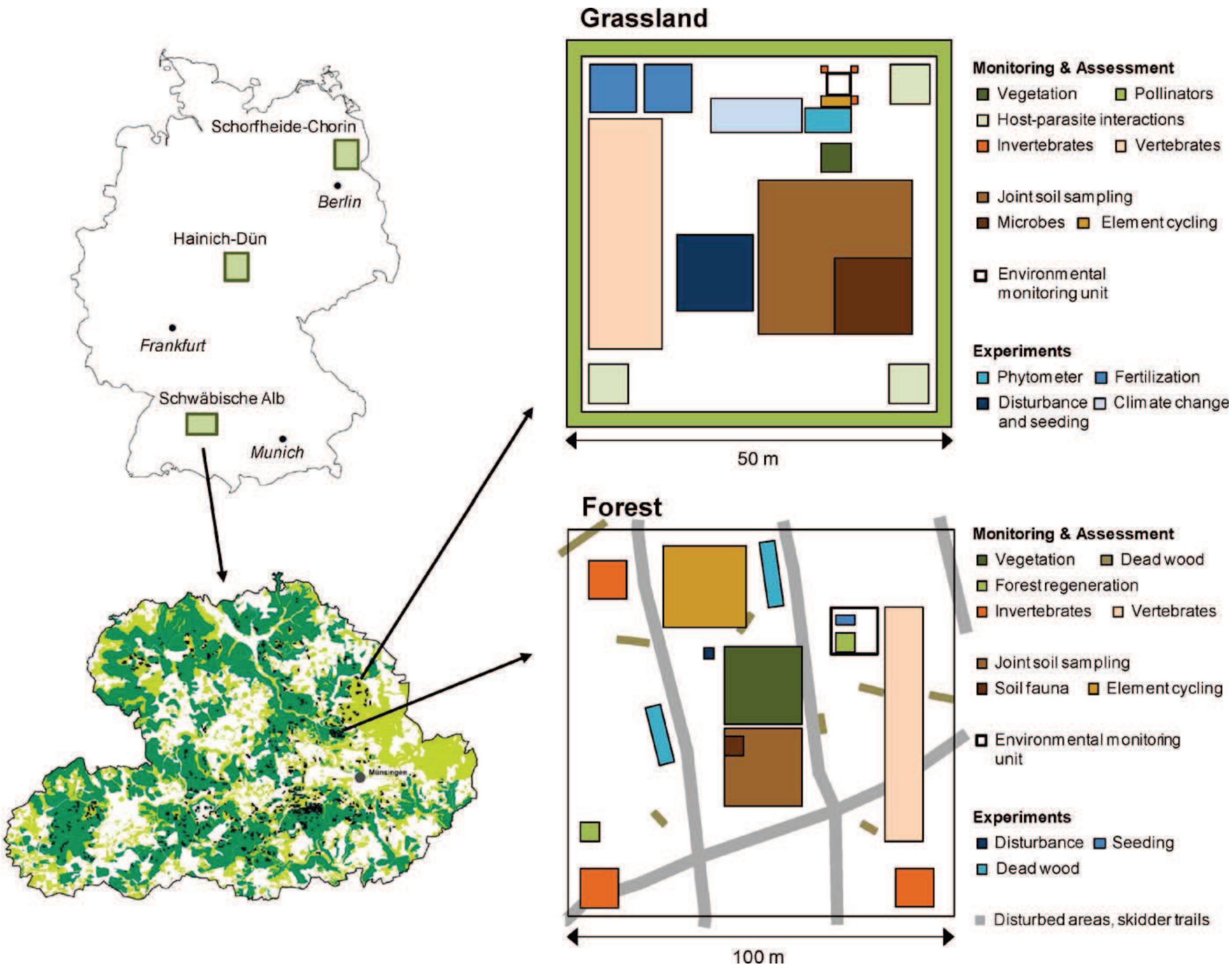

Fig. 1. Geographic location of the three Biodiversity Exploratories in Germany, a map of the exploratory Schwäbische Alb, and examples of two ‘very intensive plots’ in grasslands and forests. In the plot charts, the subplots associated with various projects are shown in different colours.

Table 2. Frequency of land use types in grassland grid plots (GPs), experimental plots (EPs) and very intensive plots (VIPs) in the three Biodiversity Exploratories in 2006/2007 as assessed during the plot selection process. One of the unfertilised very intensive plots in a pasture of the Hainich-Dün exploratory had received a very small amount of manure in 2006, but remained unfertilized ever since.

	Schorfheide-Chorin			Hainich-Dün			Schwäbische Alb		
	GP	EP	VIP	GP	EP	VIP	GP	EP	VIP
Meadows									
Fertilized	91	7	3	69	7	3	155	18	3
Unfertilized	178	11	–	12	–	–	8	4	–
Pastures									
Fertilized	25	–	–	11	2	–	34	2	
Unfertilized	131	22	3	171	18	3	135	17	3
Mown pastures									
Fertilized	15	3	–	165	15	3	94	9	3
Unfertilized	69	7	3	42	8	–	9	–	–
Fallow	38	–	–	14	–	–	–	–	–

Table 3. Frequency of land use types in forest grid plots (GPs), experimental plots (EPs) and very intensive plots (VIPs) in the three Biodiversity Exploratories in 2006/2007 as assessed during the plot selection process. In a few of the otherwise unmanaged forest plots in the Schwäbische Alb some treelets had been removed recently. As this intervention was very minor, we classified these plots as unmanaged. For age class forests the dominant tree species is indicated in the table. The 22 pine age class forests in experimental plots in the Schorfheide-Chorin exploratory comprise 15 pure pine stands and 7 pine stands where beech has been added later.

	Schorfheide-Chorin			Hainich-Dün			Schwäbische Alb		
	GP	EP	VIP	GP	EP	VIP	GP	EP	VIP
Unmanaged forest	65	5	3	81	13	3	33	5	3
Age class forest									
Beech	176	16	3	308	24	3	244	33	3
Oak	58	7	–	6	–	–	4	–	–
Spruce	10	–	–	35	4	3	130	12	3
Pine	251	22	3	–	–	–	10		–
Other species	46	–	–	58	–	–	50	–	–
Selection forest	–	–	–	70	9	3	75	–	–

The three Exploratories

As a first step for establishing the Biodiversity Exploratories, we selected three study regions: (1) the UNESCO Biosphere Reserve Schorfheide-Chorin, which is situated in the lowlands of North-eastern Germany, a young glacial landscape with many wetlands, (2) the National Park Hainich and its surrounding areas, situated in the hilly lands of Central Germany, and (3) the UNESCO Biosphere Reserve Schwäbische Alb (Swabian Jura), which is situated in the low mountain ranges of South-western Germany (Table 1, Fig. 1). Each of these areas represents most of the variation in land use typical for grasslands and forests in Germany, from hardly managed grasslands and unmanaged beech forests to highly fertilized and intensively used meadows and pastures, and intensively managed forests (Tables 2 and 3).

Selection of grid plots

To select the grid plots within each exploratory, we first used several sources of information – aerial images, different types of maps, vegetation surveys and forest inventories – to construct coarse distribution maps of habitats and land use types in each region. After that, a virtual 100 × 100 m grid was placed over the entire area, and all grid plots (i.e. cells enclosed by grid lines) covering forests or grasslands were identified. We generally discarded grid plots with inhomogeneous land cover or partial overlap with settlements, agricultural fields, water bodies and plots intersected by roads. From the remaining pool of candidate plots we selected at least 500 grid plots in forests and 500 in grasslands in each exploratory (Tables 2 and 3), which reflected the range of land use types and land use intensities in grasslands and forests, and which were confirmed to be covered by the designated land use type during field surveys. Since we aimed both at including plots of all major grassland and forest types and at representing the existing range of land use intensities, each with a certain minimum number of plots, the grid plots are not a random sample of grassland and forest habitats within each exploratory. Of course, when necessary, data from the grid plots can be used together with data on the relative proportion of land use types in the whole exploratory area to provide area-wide estimates.

For each of the selected grid plots, we collected data about key environmental variables such as slope, orientation, relief, and altitude, and we conducted a soil and a land use inventory (see below) as well as a vegetation survey. In addition, to assess the potential suitability of plots for experimental studies, we examined the homogeneity of vegetation and land use and distance to other habitat types, and the chances for obtaining the necessary permission from the land owner. Later, all this information was used for selecting the experimental plots considering land use and soil type. In particular, we aimed at avoiding confounding of soil type with land use because soil quality very often determines how land is used.

Soil inventory

To survey soil conditions in the grid plots, we conducted a standardized soil inventory. One soil sample was taken in the centre of each of the 3000 grid plots. Mineral soils were sampled with a motor-driven, 8 cm wide soil column cylinder (Eijkelkamp, Giesbeek, Netherlands) that allowed us to take largely undisturbed samples. At forest plots, the organic layer was removed with a 20 × 20 cm metal frame prior to sampling. In the Schorfheide-Chorin, organic soils could not be sampled with a motor-driven soil column cylinder because of the high groundwater tables. Instead, we used a split-tube sampler (Eijkelkamp, Giesbeek, Netherlands) to take undisturbed manual samples of the upper 30 cm of soil, and a peat sampler (Eijkelkamp, Giesbeek, Netherlands) to sample the underlying horizons to a depth of 100 cm. Additionally, we estimated the thickness of the organic layer. We described the soil type of all soil cores according to the German soil classification system (Ad-Hoc-Arbeitsgruppe Boden 2005) and the World Reference Base of Soil Resources (IUSS Working Group WRB 2006).

For more detailed soil physical and chemical analysis, we divided each soil core into several depth increments (0–10, 10–30, 30–50, 50–70, 70–90, 90–110 cm), and analysed these separately for bulk density, pH, as well as carbon and nitrogen contents. These data were not used for initial plot selection, but they will be available to analyse effects of land use on ecosystem processes (e.g. Grüneberg, Schöning, Kalko, & Weisser 2010) or soil effects on biodiversity.

It is not surprising that, because of their different parent materials, the three exploratories are characterised by different spectra of soil types (Table 4). In the Schorfheide-Chorin exploratory, the dominant geological substrate is glacial till, often covered by glacio-fluvial or aeolian sand. As a consequence, many forest soils have a texture from sandy loam to pure sand. About 70% of the forest soils in Schorfheide-Chorin are Dystric Cambisols. Less frequent are Albeluvisols, Podzols, and Regosols. The grasslands in Schorfheide-Chorin are dominated by fertile loamy soils and drained Histosols or Gleysols. In the Hainich-Dün exploratory, the dominant geological substrate is loess over Triassic limestone. Thus, both forest and grassland soils frequently have a loamy or clayey texture, and the main soil groups are Eutric Cambisols, Luvisols, and Stagnosols. In the Schwäbische Alb exploratory, soils developed mostly on Jurassic shell limestone, and they are therefore extremely rich in clay. Eutric Cambisols and Leptosols dominate in forests and grasslands.

Soil types in the Biodiversity Exploratories are not only determined by geological substrate, but also by aeolian loess layers, relief and other environmental factors. In the Schwäbische Alb, for instance, Leptosols are usually associated with steep slopes, and 10% of the grassland soils are Anthrosols, which indicates they have formerly been used as arable fields.

Inevitably, soil types are often partly correlated with present and past land use. For instance, slopes with shallow soils are usually used as sheep pastures in the Schwäbische Alb because they do not support more intensive types of land use. Not all forest land use intensities from near-natural to intensively used are found on Cambisols in the Hainich-Dün exploratory, while they are found on Stagnosols. Extremely sandy soils are frequently associated with pine forests in Schorfheide-Chorin. Since soil type and land use type usually are not entirely independent of each other, it is important to assess their correlation and to consider both factors together when examining their effects on biodiversity and ecosystem processes.

Soil properties can vary at small scales, and one soil sample per plot is therefore not sufficient to fully capture the natural heterogeneity of soils in the field. Therefore, characterising soil heterogeneity constitutes an important future task in particular for the experimental plots where most research is carried out.

Table 4. Frequencies of the main soil types in grid plots (GPs), experimental plots (EPs) and very intensive plots (VIPs) of the Biodiversity Exploratories, following the classification of the World Reference Base of Soil Resources.

Soil type	Schorfheide-Chorin						Hainich-Dün						Schwäbische Alb					
	Forest			Grassland			Forest			Grassland			Forest			Grassland		
	GP	EP	VIP	GP	EP	VIP	GP	EP	VIP	GP	EP	VIP	GP	EP	VIP	GP	EP	VIP
Albeluvisol	64	4	1	38	7	–	17	–	–	1	–	–	–	–	–	–	–	–
Anthrosol	–	–	–	11	–	–	–	–	–	20	–	–	–	–	–	32	–	–
Cambisol	407	43	8	70	7	–	110	–	–	242	28	1	289	26	6	242	15	9
Fluvisol	–	–	–	–	–	–	–	–	–	5	–	–	–	–	–	–	–	–
Gleysol	4	–	–	22	8	2	48	–	–	20	–	–	–	–	–	5	–	–
Histosol	5	–	–	327	19	7	–	–	–	–	–	–	–	–	–	3	–	–
Leptosol	–	–	–	–	–	–	–	–	–	33	–	–	286	24	3	222	35	–
Luvisol	14	–	–	35	9	–	185	37	9	47	–	–	15	–	–	–	–	–
Podzol	40	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Regosol	36	2	–	2	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Stagnosol	28	–	–	2	–	–	113	13	3	99	18	6	3	–	–	4	–	–
Vertisol	–	–	–	–	–	–	18	–	–	33	4	2	–	–	–	17	–	–
Total	598	50	9	507	50	9	491	50	9	500	50	9	593	50	9	525	50	9

Land use inventory in grasslands

To enquire the land use of grassland grid plots, we developed a questionnaire for all land owners and land users. This questionnaire covered all relevant information about type and intensity of annual land use, and further details about plot-related agricultural practices, agri-environmental schemes, socio-economic variables and plot history. For protected areas, we also enquired conservation measures. The main land use inventory of all grassland grid plots was done once, for the reference year 2006, and this information was used for the selection of experimental plots. Since land-use intensity may vary across years (particularly in the Schorfheide-Chorin exploratory farmers frequently alternate between mowing and grazing), we are repeating the land use inventory in all grassland experimental plots annually.

Grasslands fall into four main land use categories: meadows, pastures, mown pastures, and fallow land (Table 2). Mown pastures are grasslands that are both mown and grazed within the same year. For meadows and mown pastures, the questionnaire recorded the number of cuts per year and estimated the amount of hay or silage produced. For pastures and mown pastures, we recorded livestock species (cattle, horse, sheep, or goat), the type of grazing system (permanent, rationed or rotational pastures), and the estimated annual duration of grazing. In addition, to relate grazing data to livestock units we collected data about the age and density of the livestock (cattle < 1 year: 0.3 livestock units (LU), cattle 2 years: 0.6 LU, cattle > 2 years: 1 LU, sheep and goat < 1 year: 0.05 LU, sheep and goat > 1 year: 0.1 LU, horse < 3 years: 0.7 LU, horse > 3 years: 1.1 LU). For cattle pastures, we also distinguished dairy, beef production, and breeding purposes. For all grasslands, we further recorded whether they were fertilized or not, the kind of fertilizer (mineral fertilizer or organic fertilizer such as manure or dung), and the estimated annual amount of added fertilizer.

In addition to these basic data about mowing, grazing and fertilisation, we also enquired more special management measures such as drainage, levelling, harrowing, seed addition, hand weeding, or pesticide application. We also asked whether land use type had changed during the past 5 years, and whether plots had been used for agriculture during the past 20 years. Finally, for each involved farm, we enquired farm size, organizational form (private farms or farm cooperatives), number of employees, and the type of subsidies received.

On average across the three exploratories, 35% of the grassland grid plots were meadows, 35% were pastures, 27% were mown pastures, and 3% were fallow land (Table 2). Around two-thirds of the meadows and mown pastures were fertilized, but only 15% of the pastures. Mown pastures were mostly grazed by cattle, and less frequently by sheep. Pastures, in contrast, were more equally grazed by cattle and sheep. Both pastures and mown pastures were only occasionally grazed by horses. While sheep pastures were about equally frequent in the Hainich-Dün and Schwäbische Alb exploratories, almost all pastures in the Schorfheide-Chorin were grazed by cattle (see Appendix A: Table 1 for land use details of the experimental plots in grassland).

Land use inventory in forests

We assessed land use with a systematic forest inventory in all forest grid plots. This inventory was based on a circular sampling area of 500 m^2 in each plot, where we measured the diameter at breast height (DBH) and locations of all trees with DBH > 7 cm. We also recorded whether forests were unmanaged (mature forest not used (and mostly protected) for at least 60 years), age-class forests (harvested at 80–120 year intervals) or uneven-aged selection forests (trees harvested selectively). We also recorded the main tree species in each plot, and the developmental stage (bare land, thicket stage, thicket, pole wood, young timber, old timber) for age-class forests. Further, we recorded stand structure, canopy density, frequency of disturbances, and the amounts of coarse and fine woody debris as structural parameters.

On average across the three exploratories, 13% of the forests in grid plots were unmanaged forests, 83% were managed age-class forests, and 4% were selection forests. In some of the otherwise unmanaged forest plots in the Schwäbische Alb some treelets had been removed recently. As this intervention was a very minor one, we classified these plots as unmanaged. The selection forests mainly occurred in Hainich-Dün, which also harboured the largest proportion of unmanaged forests (28%). Across the exploratories, the most frequent dominant tree species was beech (78% of unmanaged and 46% of age-class forests), followed by spruce (10% of age-class forests), Scots pine (7% of age-class forests) and oak (2% of age-class forests). Pine and oak forests occurred only in Schorfheide-Chorin, whereas spruce forests were restricted to the Hainich-Dün and Schwäbische Alb exploratories. Across the exploratories, some 21% of the age-class forests were mixed forests, i.e. forests with less than 70% cover of the dominant tree species. While many forest plots showed signs of management-related disturbances such as logging trails, the proportion of disturbed plots did not differ much across the exploratories (see Appendix A: Table 2 for land use details of the experimental plots in forest).

Selection of experimental plots

All environmental and land-use data described above were used to select 100 locations in each exploratory – 50 in forests and 50 in grasslands – in which we established so-called experimental plots (EPs) as platforms for more thorough biodiversity assessment, environmental monitoring, and manipulative experiments. Experimental plots have a size of 100 × 100 m in forests and 50 × 50 m in grasslands. The selection was based on a stratified random sampling, with strata representing land use and several other criteria. Two particularly important criteria were that the EPs should cover the variation in land use intensities and in soil depth found in each exploratory, as illustrated in Fig. 2 for two variables for grassland and forest, respectively. Moreover, land owners/users or regional authorities had to allow long-term studies and experiments on the plots. Additional criteria were consistency and constancy of soil type, homogeneity of land use and vegetation composition within plots, and that they should have a slope of less than 20% and not be water-logged. In the partly steep Schwäbische Alb, however, eleven forest plots and seven grassland plots had to be selected with slopes slightly greater than 20%. Further criteria were a minimum distance of 200 m between the outer edges of two EPs, and that forest EPs should be at least 100 m and grassland EPs 30 m away from the nearest forest edge.

A particularly challenging aspect of experimental plot selection was soil type. Up to ten different soil types occurred in each exploratory, and soil type variation was partly confounded with land use type. To reduce this confounding and the variation caused by soil type, we aimed to restrict experimental plots to the two most dominant and characteristic soil types in forests and grasslands, respectively, in each exploratory (Table 4). As described above, these soil types differed between the three exploratories. In the Schwäbische Alb, Cambisols and Leptosols were dominant in both forests and grasslands, and we therefore selected EPs only from these soil types. As to Cambisols, EPs were restricted to shallow Cambisols, excluding soils with chromic ("Terra fusca") horizons. In the Hainich-Dün exploratory, Luvisols and Stagnosols dominate in forests, and not all management types and spruce age-classes were available on Cambisols. Cambisols and Stagnosols dominate in grasslands. Soils are frequently characterised by argic (forests) or vertic (grasslands) horizons and stagnic properties. For the experimental plots in forests, we therefore selected Stagnic Luvisols and Luvic Stagnisols, and for the experimental plots in grasslands we selected Cambisols, Vertic Stagnosols and a few Stagnic Vertisols. In the Schorfheide-Chorin, the characteristic soil type in forests was Cambisol, so most of the experimental plots were selected on this soil type. However, in order to fully cover the land use gradient in this exploratory, we also included a few EPs on other soils (Table 4). The situation was similar in grasslands in Schorfheide-Chorin, where, in addition to the dominant Histosols and Cambisols, we also selected some EPs on Luvisols, Albeluvisols and Gleysols. We attempted to remove confounding of soil type with land use within, but not necessarily across, each of the sets of plots in grassland or forest in each exploratory. Matching between exploratories was not a main criterion as even the same soil types are not necessarily comparable between exploratories due to the different bedrocks, which lead to differeneces e.g. in soil texture and pH. When selecting EPs, we generally excluded plots that were extreme outliers (>2 s.d.) in terms of solum thickness or stone content.

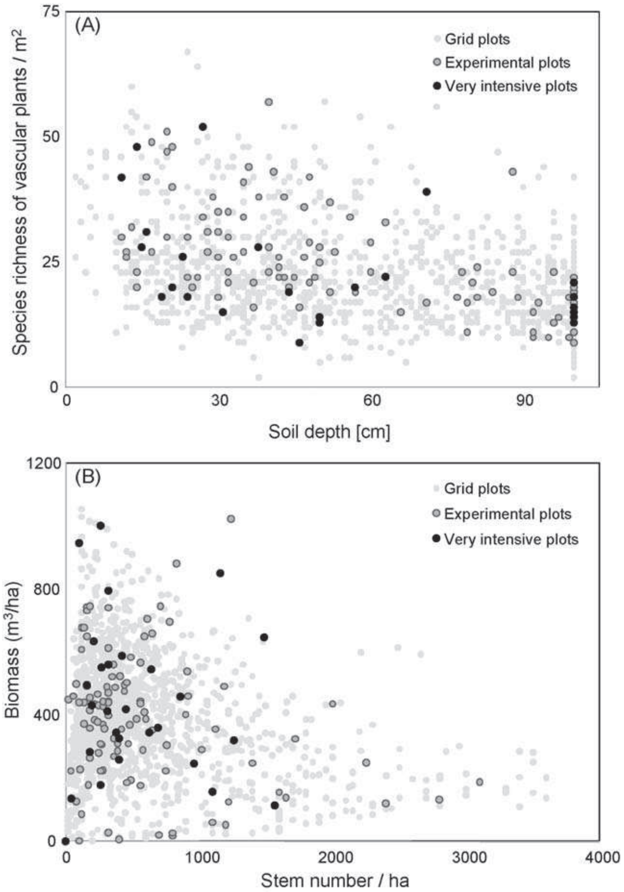

Fig. 2. The variability of study plots in the Biodiversity Exploratories, and the distribution of experimental plots and very intensive plots among grassland grid plots, illustrated by the variables soil depth and plant species richness (A), and among forest grid plots, illustrated by the variables standing biomass and stem density (B). Note that soil depth values are clustered at cut off at 100 cm, because precise values are not available beyond 100 cm for all of these plots. Nevertheless, for many of these plots, the soil depth is above 100 cm.

Selection of 'very intensive plots'

Of the 100 experimental plots in each exploratory, we further selected a subset of 18 plots – nine in forests and nine in grasslands, three per specific land use type and region (Tables 2 and 3) – which we called very intensive plots (VIPs), for applying methods too labour-intensive to be done on all EPs. One example of such VIP research, with the goal to establish the method and to extend measurements in the future to all experimental plots, is the detailed assessment of soil microbial diversity with molecular methods. To cover the available range of land use intensities, we generally selected the VIPs equally from three land use types of increasing land use intensity. In grasslands we selected three VIPs from each, unfertilized pastures, strongly fertilized meadows, and mown pastures, which were unfertilized in Schorfheide-Chorin and fertilized in the Schwäbische Alb and Hainich-Dün (Table 2). In forests we selected VIPs from natural forests, age-class forests, and conifer plantations (Table 3). In the Hainich-Dün exploratory, we additionally included three VIPs in selection forests, because this forest management is very important in this region.

Plot implementation and instrumentation

We marked each experimental plot with subterranean metal ties, and recorded their exact position in early 2008. To facilitate orientation, we created detailed charts of each plot, which also contained the precise locations of forest tracks or any other kind of disturbance on or close to the plots. The maps were later digitized to create the interactive plot maps now available in the database (see below). A key feature of the exploratories is that the research activities do not affect the ongoing land use.

To measure climatic conditions in the Biodiversity Exploratories, we set up 300 environmental monitoring units in all experimental plots. The basic environmental sensors installed in all EPs measure air temperature (nominal precision: ±0.3 K) and relative air humidity (±1%) at 2 m above ground, soil surface temperature (±0.1 K) at 10 cm above ground, soil temperature (±0.1 K) at 5, 10, 20 and 50 cm below ground, and soil moisture (±1% VWC) at 10 cm below ground. VIPs have a second soil moisture sensor which additionally measures soil moisture at a depth of 20 cm. All measurements are taken hourly, and all systems are working with data loggers (ADL-MX, Meier-NT, Zwönitz, Germany).

To also obtain information on variation in wind speed and direction, precipitation, solar radiation and barometric pressure, we are currently equipping nine experimental plots per exploratory, geographically spread over the whole exploratory area, with additional sensors. In addition, we are implementing one tower in closed beech forest in each exploratory (and an additional one in Hainich-Dün), which will measure climatic variables also above canopy level.

Management structure

The Biodiversity Exploratories are a research platform for currently over 40 projects involving more than 300 people – equally divided between scientists, students and technical staff – with a wide range of scientific backgrounds and approaches. The success and synergistic effect of such a large and diverse project largely depends on an efficient management structure. The project is led by a steering committee of six senior scientists, headed by a project speaker. Each of the three exploratories is managed by a local team consisting of a manager, a forester, an engineer, and two further technical staff. These local management teams are responsible for the set-up and maintenance of field plots and technical facilities, they advise researchers about practical and administrative issues in the exploratory, and they keep contacts with local stakeholders. All scientific activities are coordinated by the central project office (Biodiversity Exploratory Office) as approved by the steering committee. This office also assists with project administration, facilitates communication among management teams and research groups, organizes training courses for all PhD students, and it is responsible for PR and outreach.

Although individual research projects in the Biodiversity Exploratories typically last for 3 years, the platform has been designed as a long-term infrastructure. Therefore, to ensure long-term consistency and integrity of the project, a set of common rules for data and publication policy, as well as for conduct in the field have been established, which all project members must acknowledge by signature to obtain the necessary field permits.

Database

To facilitate the compilation and dissemination of information and data across the different working groups, we set up a central database, which serves both as central data storage facility and as work-in-progress database actively used by all researchers in the Biodiversity Exploratories including an interactive platform for coordinating field work, managing field plots, and distributing practical and administrative information among project participants.

To support field work, the database provides basic information such as photographs and directions for each plot, a WebGIS (Dragicevic 2004; Mückschel, Schachtel, Nieschulze, & Köhler 2004) for orientation in the field, detailed interactive maps of each plot (see Fig. 1 for examples), and an online booking system for field accommodations and facilities. All changes in the database are logged, so the database also functions as an archive.

The database sensu stricto, i.e. the part containing data and meta-data, employs XML technologies (W3C 2003) for data harmonization across the involved disciplines. XML allows for a formalized yet flexible description of metadata, data formats and syntaxes, which were determined prior to the first field season. The coverage of many different data formats and structures is essential for acceptance by the user community. Usage is further facilitated by web-service interfaces (Heimann, Nieschulze, & König-Ries 2010) that can be read by the statistical package R (R Development Core Team 2008).

Core and contributing projects

The research in the Biodiversity Exploratories is organised into core and contributing projects. Starting in 2006, six core projects carried out the environmental, soil and land use inventories described above, selected experimental and very intensive plots, and implemented the necessary technical and administrative infrastructure for the project. Moreover, the core projects are ensuring consistent long-term monitoring of the species diversity of selected taxa of plants, fungi, birds, bats and other mammals, selected insect taxa and microorganisms, and they assess genetic diversity of selected taxa of plants and microorganisms. The core projects address selected ecosystem processes and services including pools of biomass and carbon, pollination services, predation, seed dispersal and community stability and are also carrying out experimental studies. These include experiments manipulating deadwood availability in the very intensive forest plots, fencing off subplots of all forest experimental plots to exclude large herbivores, and increasing plant species diversity by seeding in subplots of the grassland experimental plots.

Currently, 34 contributing projects are addressing the genetic and species diversity of many taxa, including soil organisms, ecosystem processes related to nutrients, food webs and pollination webs, and modelling of species interactions and ecosystem processes in relation to land use (Appendix A: Table 3). Where possible, all core and contributing projects are doing research on all experimental plots. Only those activities, for which this is not possible, are limited to the very intensive plots. Moreover, many of the contributing projects have experimental components replicated across all very intensive plots or all experimental plots. Working on the same plots guarantees standardization of the study design and enables quantitative synergy by data synthesis within and across projects. For research groups working on soil organisms, common soil samples were taken in a coordinated effort, during which soil or extracted DNA was distributed to the involved groups, in order to minimize sampling heterogeneity. More detailed information about the research in the Biodiversity Exploratories is provided in Appendix A: Table 3 and on http://www.biodiversity-exploratories.de/Projects.

Conclusions from the Biodiversity Exploratories for functional biodiversity research

We are developing the Biodiversity Exploratories as an exemplary research platform for addressing feedback loops between land use, biodiversity change, and their consequences for ecosystem functioning and ecosystem services. Common guiding questions (Lindenmayer & Likens 2009) and the combination of monitoring of biodiversity and ecosystem measures with manipulative experiments in a common study design with replicated sites are essential for overcoming the disciplinary separation that is hampering our comprehensive understanding of drivers and functional consequences of all facets of biodiversity. Working on common plots ensures that a common language is used by the involved researchers and allows for quantitative data synthesis, two key elements in the integration of the strong but scattered research communities of the different biodiversity and ecosystem research disciplines. At the same time, it is an essential requirement for the training of a new generation of biodiversity explorers (Fischer, Schreier, & Larigauderie 1997). In addition to the spatial scale with many replicated sites in very different regions, the temporal scale with a planned duration of more than 10 years is essential for capturing trends in the occurrence and abundance of different taxa and temporal interactions between taxa and processes.

The concept of the Biodiversity Exploratories can be extended to other landscapes and habitat types, such as croplands, landscapes with freshwater bodies, urban systems, coasts or alpine landscapes. An interesting challenge is posed by integrating landscape features surrounding the study plots, such as the type and areal proportion of habitat types, or regional topography and climate. Further challenges include the quantification of land-use intensity, a concept which is the more difficult to define and apply the more diverse the types of land use are which are employed in a study area.

In Europe, a number of environmental monitoring programs and initiatives are addressing parts of the land use-biodiversity-ecosystem process research agenda (Hammen et al. 2010). The long-term ecological research network LTER-Europe combines a diverse array of ecological research sites, where biodiversity research is among several research foci in some of the sites (Müller, Baessler, Schubert, & Klotz 2010). Further initiatives are addressing parts of the land use-biodiversity-ecosystem process research agenda outside Europe (North America (e.g. Keller, Schimel, Hargrove, & Hoffman 2008), South America (e.g. Joly et al. 2010), Africa (e.g. Reyers & McGeoch 2007), Asia (e.g. Sodhi, Koh, Brook, & Ng 2004), Australia (e.g. Abbott & Le Maitre 2010). In summary, there is the world-wide realization that long-term and large-scale ecological research sites are needed to address current ecological questions at the appropriate temporal and spatial scale.

The key messages of the Biodiversity Exploratories for any larger-scale efforts to monitor and understand the relationships between drivers and functional consequences of biodiversity change are:

(1) consider all land uses and climatic conditions,
(2) consider all taxa, their genetic diversity, species diversity and interaction diversity, and the relationships among these facets of biodiversity,
(3) consider all relevant ecosystem processes and services, including means and variation of pools and fluxes in biogeochemical cycles as well as biotic processes and services including pollination, dispersal, predation,
(4) reflect all these issues by involving the corresponding research disciplines in a common framework guided by overarching questions and through a jointly used network of replicated field plots.

In our opinion, an extended network of exploratory-like research platforms across Europe and the world capturing the main types of ecosystems would allow for much more mechanistic understanding and prediction of changes in biodiversity and ecosystem function than the manifold and very scattered activities currently going on. Therefore we suggest integrating such platforms into a future global network of biodiversity observation systems, as envisaged by The Group on Earth Observations Biodiversity Observation Network (GEOBON, Scholes et al. 2008). We hope that the concept and example of the Biodiversity Exploratories contributes to stimulating functional biodiversity research in realistic landscape contexts in Germany and globally.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.baae.2010.07.009.

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