Long-Term Ecological Research at Gobabeb: gaining and applying knowledge about a highly variable environment

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Zusammenfassung

Abstract

Long-term ecological research (LTER) is valuable for understanding environmental processes in arid countries like Namibia. It is also essential for effective natural resource management. Using a wealth of knowledge accumulated over the years in the Central Namib Desert and, more recently, in rural communal areas in western Namibia, the Desert Research Foundation of Namibia (DRFN) is using LTER to connect basic and applied research in an appropriate manner. Various projects concern climate, the biophysical environment, plants, animals, and people. Examples are given of how these projects are interrelated and how they serve many social and environmental functions in rural Namibia. The formation of a national Namibian LTER network, and Namibia's membership in the International Long Term Ecological Research Network affect the future of LTER conducted by DRFN and other Namibian organisations.

Introduction

The Desert Research Foundation of Namibia at the Gobabeb Training and Research Centre, situated in the Central Namib, has set itself the goal of increasing understanding of a hyperarid environment, especially its variability, that can be applied to other variable environments to help reduce the latter's vulnerability to loss of sustainable livelihoods (SEELY *et al.*, this volume). One of the major means of increasing understanding, is through Long Term Ecological Research (LTER), continuous or periodic monitoring combined with detailed short-term studies of numerous environmental aspects. By conducting LTER in the Namib Desert, a hyperarid region, it is possible to understand the effects of extreme hydrological variability, and to apply this knowledge appropriately in line with the above-stated goal.

Understanding natural environmental variability is important for environmental management (LANDRES *et al.*, 1999). Tropical arid and semi-arid regions like those characterising much of Namibia experience extreme temporal and spatial variation of rainfall (TYSON, 1986; NICHOLS and WONG, 1990) due to the negative correlation between rainfall variability and aridity (TYSON and DYER, 1975; Fig.1). In arid regions, brief episodic events affect long-term processes (CRAWFORD and GOSZ, 1982; WEATHERHEAD, 1986). In particular, heavy rainfall events elicit dramatic responses (SEELY and LOUW, 1980; NOY-MEIR, 1981), have effects lasting for decades (WALTER, 1971; SOUTHGATE *et al.*, 1996; HENSCHEL, SEELY and POLIS, 1998), and are thus prominent ecosystem drivers. Furthermore, there is high spatial variability of rainfall in arid regions (DEAN and MILTON, 1999; WARD and ELLIS, 1999; Fig. 1). This leads to spatial concentration of resource production, and rich patches can affect large resource-poor areas, i.e. populations in rich patches are sources for surrounding sink populations that are sustained by them (PULLIAM, 1988; WATSON and SUTHERLAND, 1995; DIAS, 1996). Rich patches arise, expand, shift and contract dynamically at variable rates (JELTSCH *et al.*, 1998; MILTON, 1995; REYNOLDS *et al.*, 1999). Biotic responses to temporal and spatial variability may depend either on pulses and sources, i.e. irruption, or on tolerance of reserve and sink conditions, i.e. persistence. These responses affect and are affected by people, and it is therefore important to understand natural variability in order to facilitate appropriate environmental management (LANDRES *et al.*, 1999).

Long-term Ecological Research (LTER) enables one to recognise and elucidate natural patterns of temporal and spatial variability and changes in such patterns (RISSER, 1995). LTER integrates the findings of continuous or periodic environmental monitoring with short, experimental studies. LTER focuses on time spans of decades to a century, and encompasses historic records inasmuch as they are based on measures that are repeatable (ILTER, 2000). While paleoclimatological and archaeological research makes inferences on environmental and anthropogenic changes over time spans of centuries to millions of years, more direct measurements are required to understand the complex patterns and factors underlying environmental variability and changes during present times and the past century. During the latter time span, it is not only possible to elucidate complexity, but also possible to influence the outcome, as this time span encompasses funding cycles of projects, legislative periods of governments, and the generations and lifetimes of people. LTER covers this time span and it can thus provide researchers, resource managers, and policy makers with data needed to detect, quantify, locate, understand and respond to changes in terrestrial ecosystems so as to support sustainable development (GTOS, 2000). SEELY (1998), SEELY and JACOBSON

(1994) and SEELY *et al.* (submitted) outline how this connection between science and development serves creative problem solving in Namibia.

LTER provides baseline data on long-term environmental processes, including responses to episodic events. It facilitates the interpretation of short-term studies, and it provides the connecting framework between different studies. LTER can record environmental changes caused by human activities and elucidate factors affecting people, combining biophysical with socio-economic data. These data do not only support a theoretical framework, but are an invaluable source of information for generating environmental awareness, influencing decision-makers, and training students in environmental fields. LTER is therefore an invaluable tool to guide the development process in Namibia.

In August 1999, Namibia formed a national LTER network (Na-LTER, 2000) and became the first country in Africa to join the International Long-Term Network, ILTER (HENSCHEL, 1999). ILTER is a growing global network comprising countries around the world that co-ordinate and share research efforts and results through this network (FRANKLIN *et al.*, 1990; RISSER, 1995; GOSZ, 1996; ILTER, 1999, 2000). Allied to ILTER, the Global Terrestrial Observation System (GTOS, 2000) also endeavours to improve the sharing of information and data on sites being monitored globally on a long-term basis. Na-LTER is connected to these international networks so as to facilitate the sharing of data, information and experience in both directions, especially so as to achieve value-addition through such collaboration.

The purpose of the Namibian Na-LTER network is that its partners have increased capacity to provide, access, understand and use long-term ecological data and information in Namibia (Na-LTER, 2000). The Na-LTER network comprises institutions and researchers willing to contribute to its goals, purpose and objectives. Na-LTER endeavours to identify, promote and facilitate the appropriate operation of sites where long-term environmental monitoring and analyses are conducted. A core facility of Na-LTER is planned to be a Metadatabase, comprising information on data, namely what the data concern, where, when, and by whom they were obtained, how and where others can obtain copies, conditions of use, and other details.

Gobabeb is a national Na-LTER and international ILTER site, where the LTER programme, conducted in collaboration with many institutions, forms part of the institutional programme of the Desert Research Foundation of Namibia (SEELY *et al.*, this volume). The premise for the joint venture agreement on the Gobabeb Training and Research Centre between MET and DRFN provides this site with the collaborative spirit that is central to LTER. Other Namibian LTER sites are part of monitoring programmes in the Etosha National Park (e.g. Etosha Ecological Institute), and at agricultural, forestry and university research stations. Yet another type are LTER sites that are not directly affiliated to on-site research stations, e.g., parks, reserves, and conservancies, weather stations, hydrological monitoring points, coastal and other wetlands, river catchments, the Eastern National Water Carrier, Inselbergs, desertification programme study sites, Sardep agricultural study sites, Rehoboth Acacia Forest, Polytechnic field sites, and those of foreign programmes, such as BIOTA. A further type are other regional or site-specific data shared through the Na-LTER network, such as socio-economic monitoring by NEPRU (Namibian Economic Policy Research Unit), livestock censuses by Veterinary Services, wildlife censuses by Directorate of Specialist Support Services, as well as runoff and groundwater monitoring by Department of Water Affairs.

In this paper we describe the LTER programme co-ordinated by the DRFN at Gobabeb. We also show how LTER is being extended and applied in different ways since Independence (SEELY *et al.*, submitted). Thirty-eight years of research in the Namib (since 1962) has enabled the DRFN to gain significant knowledge on environmental processes under arid conditions (Henschel *et al.*, 2000). Since Independence, this knowledge is being used to further environmental awareness and to promote the capacity to manage the Namibian environment appropriately. This is addressed through research, information and training programmes that focus environmental fields such as climatic variability and its influence on the environment, ephemeral rivers and their catchments, and desertification. LTER is fundamental to these programmes, and this paper focuses on its biophysical and socio-economic aspects. Besides strong applications for training, we emphasise the importance of involving people, not only to raise awareness, but also to facilitate the process by which rural communities become an integral part of monitoring and managing the environment in Namibia.

This paper does not attempt to provide a comprehensive review of the application of the knowledge gained through LTER at Gobabeb, nor of research in the Namib where numerous other organisations are involved. Besides describing the Gobabeb LTER programme, we provide examples of how the DRFN and its associated students and scientists are applying information derived from it, as well as setting up monitoring sites in the areas of application.

Study Areas and General Methods

LTER around the Gobabeb Training and Research Centre (23°33'S; 15°02'E) encompasses several sites in the Central Namib Desert. Study sites are in the three major habitats characterising the Central Namib, on the gravel plains, in the Kuiseb riverbed and in the dunefield of the Great Sand Sea. The general climatic, geological, geomorphological and ecological conditions were described e.g. by BESLER (1972a), GOUDIE (1972), ROBINSON (1978), ROBINSON and SEELY (1980), LANCASTER *et al.* (1984) and SEELY (1990a). Study sites are monitored at regular intervals, varying between projects from daily to monthly, seasonally, annually, or at intervals of several years. Some projects were initiated by short-term research projects when the methods and monitoring protocol were established. Monitoring then continued after the publication of initial results identified the potential value of long-term data.

The sites of the Namibian Programme to Combat Desertification (NAPCOD) where DRFN has initiated studies that can continue with LTER are situated in the communal and commercial farming areas of the former Damaraland in north-western Namibia (Kunene Region). This and other farming areas of Namibia, not described here, form part of the NAPCOD-III programme (ZEIDLER, 2000). The north-west sites include farms with a background of commercial, communal and alternating commercial/communal land tenure that depended on changing land tenure policies under different governments (KAMBATUKU, 1996; ZEIDLER, 1999). In the current paper we use one of the communal farms, Olifantputs (20°26'S; 14°96'E), as example. LTER at the NAPCOD sites follows the guiding principles of the Convention to Combat Desertification (CCD), such as conducting participatory, community-based and community-relevant research (UNEP, 1995). Besides the establishment of ecological monitoring programmes focusing on climatic, vegetative, soil-related and biotic components of the environment, it is important to monitor aspects relating to people, such as the history of land use practices (KAMBATUKU, 1996), population dynamics and migratory patterns of people and livestock, changes in the use of natural resources, and lifestyles (ZEIDLER *et al.*, 1998; ZEIDLER, 1999). The local farmers are actively involved with the DRFN in the collection, management, and interpretation of data.

The Projects

Table 1 summarises the different research foci and trajectories referred to in this section.

Climate

Long-term weather data are fundamental to the understanding of a highly variable environment such as the Namib. At Gobabeb, weather has been recorded continuously since 1962 at the First Order Weather Station of the Namibian Meteorological Services. Furthermore, DRFN operates a network of autographic weather stations covering an area of 10 000 km^2. Of the 45 stations, there are eight main ones that are operated continuously and cover the width of the Namib from near the coast (Radio Station "33" 10 km east of Walvis Bay, at an altitude of 40 m above mean sea level) up to above the Great Escarpment (Farm Weissenfels, 10 km east of the Gamsberg, altitude 1800 m above mean sea level). These weather stations are fitted with electronic data loggers and software that transcribe data at hourly intervals and are monthly copied to computer (Mike Cotton Systems, Steenberg, South Africa). Other organisations that also operate weather stations in the Namib include the Namibian Meteorological Services (several manually and automatic stations along the entire Namib coast) and the University of Cologne (several weather stations between Swakopmund and Usakos).

The surface weather records of the DRFN have been used to characterise Namib climate (LANCASTER *et al.*, 1984). They have documented episodic events, such as rare, heavy rainfall, or a poor fog season, heavy sand storm, or heat wave. For example, the sources of surface water at Gobabeb differ in their variability. Fog from the Atlantic Ocean is the most regular source (mean = 39 mm per annum; CV = 43%), while rain is sporadic (21.2 mm; CV = 122%). Runoff in the ephemeral Kuiseb river from rainfall in the inland catchment in the Khomashochland occurs nearly every year, but differs in duration (18 days; CV = 150%). Variability in rainfall differs across the Namib (Fig.1), and this is very important for understanding the composition of biotic communities, the distribution of organisms and their life history patterns (HOLM, 1970; ROBINSON, 1978; SEELY, 1973, 1978a, b, 1990b; SEELY and LOUW, 1980; NEL, 1983; HAMILTON, 1985, 1986; TILSON and HENSCHEL, 1986; YEATON, 1988; BOYER, 1989; BERRY and SIEGFRIED, 1991; GÜNSTER, 1993, 1995; BRAIN, 1993; KILIAN, 1995; KOK and NEL, 1996; SOUTHGATE *et al.*, 1996; HACHFELD, 1996; JACOBSON, 1996, 1997a; BURKE, 1997; JACOBSON and JACOBSON, 1998; HENSCHEL, SEELY and POLIS, 1998; HENSCHEL and SEELY, in press). Micro-climate varies between habitats and this has been monitored at several sites around Gobabeb. Most of the research and training at Gobabeb incorporates one or the other climatic or micro-climatic aspect, and it is seen as the common thread that links most fields. Climate is among the fundamental factors required for effective planning development in the region (BENDER, 1999). The many instruments and data bank at Gobabeb are invaluable tools for training. The diversity of instruments illustrate fundamental climatic principles, while the data bank allows climatologists, ecologists, geomorphologists, appropriate technologists, and students to understand these principles in the context of the spatial and temporal variability of climate.

Since the beginning of 1997, rainfall data are collected at sites in southern Kunene region by communal farmers in a participatory manner, i.e. farmers and other community members monitor the rain gauges and keep records. Data analyses and interpretation are collaborative with NAPCOD field staff. Discussions facilitate the understanding of the spatial and temporal variability of rainfall, which assist farmers in planning sustainable resource management.

As an important climatic feature of the Namib, fog has been studied over 60 years (e.g., WALTER, 1937; BOSS, 1941; LANCASTER *et al.*, 1984). In the last three years monitoring has been intensified with the aim of collecting this water source for domestic use in the western Namib Desert (HENSCHEL, MTULENI *et al.*, 1998), including gardens in Swakopmund (COETZEE and MULDER, pers.comm.). The possibility is being explored to utilise sun and wind energy for small solar stills to purify substandard water and to provide electricity to remote centres, such as Gobabeb (SHANYENGANA, 1997a, b). The LTER data series are invaluable for planning these applications.

Biophysical Environment

Dune movements – Namib dune dynamics have been monitored since 1970. Such measurements were established to monitor the geomorphological processes of dune movements *per se* as well as the relation thereof to the biotic system. It has been suggested that the high diversity of certain taxa such as tenebrionids in the Namib Desert can be explained by the mobility and changing configuration of sand dunes (ENDRÖDY-YOUNGA, 1982; PENRITH, 1986; IRISH, 1990). Populations of psammophilous animals become geographically isolated from conspecifics when their dune moves. Conversely, two dunes that were not previously connected may connect and their satellite organisms become sympatric. The Namib Great Sand Sea has many types of dunes with different configurations and dynamics changing along an east-west gradient (LANCASTER, 1989). The middle of the dunefield, including the area south of Gobabeb, is dominated by long linear dunes. Since BESLER's (1970, 1972b) initial study, DRFN has monitored the physical dynamics of one such linear dune on a monthly basis. Here, trainees can learn environmental principles such as the relationship between dune configuration, microhabitats, and associated animals and plants. Students who have been sensitised in this way are better able to recognise similar relationships in more complex environments.

Weathering – The Central Namib Desert represents a hostile environment for rock, with salt, temperature changes, fog and lichens, all known to be important weathering agents. Over time, weathering produces debris (including silt-sized material) and leaves eroded rock. This process is being studied by monitoring weathering rates and processes across an East-West transect through the Central Namib Desert over a period of many years. Changes in the micro-environmental conditions are being measured so as to elucidate their effects (GOUDIE, 1972; GOUDIE *et al.*, 1997; GOUDIE and PARKER, 1998), and assist planning of development. The deployed blocks of rock at Gobabeb is very useful for demonstrating the principles of weathering to environmental trainees.

Off-road vehicles (ORV) – The impact of ORVs on the desert surface has been monitored since 1978 (SEELY and HAMILTON, 1978; DANEEL, 1992a, b). Vehicles change the properties of soil, including the desert pavement, calcrete and gypsum crusts, as well as the biota, particularly lichens and dwarf shrubs. For example, ORVs reduce the microtopography and push stones and lichens into the soil, thereby reducing surfaces for lichens to gro on an impe ing their recovery; a fresh ORV track estroys 80% of the lichens (Daneel, 1992a). These properties take a long time to recover (Eckardt, 1996) an long-term stu ies are require to monitor recovery. Seely an Hamilton (1978) an Daneel (1992a), respectively, place control tracks in an inter une an several gravel plain areas in the Namib respectively. By monitoring these tracks at intervals of several years, e are learning about the recovery process, inclu ing that of lichen fiel s. ORV tracks enable stu ents to become sensitise to critical soil processes. At a stage hen the use of ORVs appears to be increasing in estern Namibia, this stu y provi es a goo basis for planning an for a vice on river behaviour.

Soil – Soil processes play a major role in sustaining pro uctivity of agricultural pro uction areas, inclu ing crop-lan s as ell as range systems (Greenland an Szabolcs, 1994). This is important particularly in vie of the concerns about esertification an lan   egra ation in Namibia, but also for bio iversity research because many soil processes are me iate by the soil biota (Anderson, 1994). Soil processes are being monitore at NAPCOD sites in southern Kunene region. This concerns the biological integrity of farms un er ifferent lan tenure an   ifferent lan -use intensities, ith particular emphasis on the communal farm Olifantputs. At six ifferent monitoring plots of 1 ha each, soil parameters such as nutrient status an biophysical parameters are measure t ice a year since 1997. This is one to gauge the effect of various kin s of communal an commercial farming on rangelan an habitat con ition in estern Namibia (Zeidler *et al.*, 1998; Zeidler, 1999). These ata are correlate   ith the bio iversity of soil organisms. Other long-term stu ies can be initiate by revisiting sites that ere part of other applie stu ies associate   ith Gobabeb (e.g., Ward *et al.*, 1998).

Ephemeral Rivers – For many years, the Kuiseb river ecosystem has been stu ie from the biophysical an ecological perspectives, hile it also serves as an excellent out oor classroom for stu ents ho can learn ho natural an anthropogenic processes in this linear oasis contrast ith an influence the surroun ing esert habitats. Since 1963 floo s an groun ater level have been monitore , an on several occasions since 1976, aerial photographs ere taken (e.g. Huntley, 1985; Jacobson *et al.*, 1995). The effect of changes, natural as ell as anthropogenic, on vegetation an ultimately il an   omestic animals are recor e (e.g., Hamilton *et al.*, 1977; Seely, Buskirk an Hamilton, 1980; Theron an van Rooyen, 1980; Tilson an Henschel, 1986; Gabriel, 1992; Dausab *et al.*, 1993; Zeidler, 1995; Amoomo *et al.*, 2000). Such stu ies ere the eparture point for the ephemeral rivers project that establishe similar monitoring points in other ephemeral rivers throughout north- estern Namibia uring 1994 (Jacobson *et al.*, 1995), an these are perio ically revisite . This, in turn, has given rise to a more etaile stu y of the Hoanib River Catchment (Leggett, 1998, 2000). This scientific information has been transferre into public ocuments, inclu ing vi eos an maps (e.g., Jacobson *et al.*, 1995; Heyns *et al.*, 1998). These materials a ress issues relate to the use of natural resources, explaining bio iversity an other important ecological concepts to laymen.

Plants

Welwitschia – Long-live plants are affecte by long-term processes an long-term stu y is require to un erstan these. *Welwitschia mirabilis* is a i sprea en emic of the central an northern Namib (Bornman, 1978). In some areas it is the ominant perennial plant present an may serve as shelter or foo source for various animals. As the only member of the family Welwitschiaceae, and a most unusual desert plant, the Welwitschia is a botanical curiosity and is protected by national legislation. MARSH (1982, 1987, 1990) and BRINCKMAN and VON WILLERT (1987) emphasised that it is important to know more about the phenology of this plant and its satellite fauna in order to improve the management of Welwitschia fields. Accordingly, the DRFN initiated a monitoring programme in 1985 in which the degree of leaf growth of 11 male and 10 female plants is measured at monthly intervals. Seasonal patterns are correlated with air humidity, while annual differences are affected by rainfall, but fog does not influence growth patterns and germination (HENSCHEL and SEELY, in press). The continuing study elucidates the reproductive output, seed dispersal, recruitment, water availability, age structure, and ecological differences between the sexes, and long-term life history strategies. Because of its stark differences to other plants and clear responses to environmental conditions, Welwitschia has high demonstration value for students.

!Nara – Another long-lived plant is being monitored, namely, !nara *Acanthosicyos horridus* (Cucurbitaceae), a potential keystone species of the Namib dunes (KLOPATEK and STOCK, 1994). !Nara appears to be affected by various environmental factors, such as climate, ground-water availability, herbivory and fruit harvesting, while plant condition may affect numerous invertebrates and vertebrates that feed on or shelter in it. !Nara fruits are used by the local Topnaar people as food, fodder, for medical purposes, and as a cash crop under a unique form of tenure (DENTLINGER, 1977). The Topnaar community requested advice from the DRFN on sustainable resource management of the !nara. Subsequent investigations have involved both participatory and academic research, with some of the latter being conducted by students and in-service trainees. Unpublished recent studies by DRFN and associates concern the socio-economic importance and marketing of products (BÜTTENDORF, 1999), the plant's water sources, requirements and transpiration, photosynthesis, pollination, seed dispersal, germination and seedling establishment, herbivory, and the importance of !nara for animal ecology. The !nara is an excellent training tool as it enables students to conduct a wide variety of valuable exercises, ranging from biophysical factors, to ecology and resource management.

Grass – Grass is a major source of primary productivity and detritus and forms the basis of a major food web. For example, SEELY (1990b) described the long-term development of hummocks of the perennial dune grass *Stipagrostis sabulicola*, which are being monitored at intervals of several years since 1976. Ephemeral grasses germinate and can complete their life cycle after a minimum rainfall event of 10-12 mm (SEELY, 1978a, b; JACOBSON, 1992; GÜNSTER, 1993) and the biomass increases with increasing rainfall. In most years since 1988, the annual distribution of ephemeral grasses have been monitored in the central Namib (GÜNSTER, 1995) and was found to be highly variable over space due to patchy rainfall (BURKE, 1997). This provides an excellent opportunity to elucidate the connection between spatial heterogeneity and biodiversity. Establishing this relationship would increase our endeavour to understand biodiversity in variable environments throughout Namibia (BARNARD, 1998a, b).

Plant communities – Another important LTER project entails the re-examination of all plant communities on the gravel plains of the southern Central Namib (HACHFELD, pers.comm.) over 20 years after ROBINSON's (1976) study. By comparing the spatial distribution of various plant species and of the species composition of various communities, long-term changes in community development can be determined. Furthermore, this study is providing an invaluable baseline for understanding plant biogeography (and associated fauna; e.g., WHARTON, 1980) in the Namib (HACHFELD, 1996). Similarly, re-examining mycorrhiza and lichens at existing study sites (DANEEL, 1992a; SCHIEFERSTEIN and LORIS, 1992; JACOBSON, 1997a), provide important insights into the dynamics of biotic components of the soil surface, particularly in the dunes and on the gravel plains.

On long-term monitoring plots established on three farms in southern Kunene region along gradients of different land-use intensities and different types of land tenure (see above) various vegetation parameters are monitored. These include plant species composition and annual net primary production. These are commonly used indicators of range condition (BEHNKE *et al.*, 1994) and are included in an index of biological integrity developed for Namibian rangelands by DRFN (ZEIDLER *et al.*, 1998; BARNARD *et al.*, 1999; ZEIDLER, 1999). Plants are the key to people's perceptions of their own land and affect their decisions on land use. Perceptions are therefore directly incorporated into the monitoring (ZEIDLER *et al.*, 2000).

Photography – Fixed point photography is a convenient and objective method of monitoring changes of vegetation over seasons, years and decades. This technique lends itself to qualitative and quantitative analyses (e.g. identity, number and size of plants and their relative cover). The DRFN has established fifty fixed points in the Namib and along a transect between Gobabeb and Windhoek and another similar set in southern Kunene region at all NAPCOD sites. These photographs lend themselves to very broad application, and form historical records. For example, ROHDE (1997a, b) used repeat photography, retaking of historical photographs, to identify changes in vegetation over decades to a century.

Animals

Large mammals – Knowledge of the long-term population dynamics and movements of large mammals is very important for their effective management. The Ministry of Environment and Tourism, for example, found that the distribution of gemsbok was primarily determined by the availability of water, whereas grazing affected abundance (BERRY and SIEGFRIED, 1991; KILIAN, 1995; KOK and NEL, 1996), as established through longer-term data records (NEL, 1983). It is important to continue this monitoring and it is suggested to include mountain zebra into the monitoring, as the Namib-Naukluft Park is the distribution centre of this endemic species (JOUBERT, 1974). Troops of baboons living along the Kuiseb River are being monitored at regular intervals since 1970 (HAMILTON *et al.*, 1976; HAMILTON, 1985, 1986; BRAIN, 1992) and in the Swakop River since 1990 (COWLISHAW, 1999). For baboons water is a principal limiting resource and its availability affects reproduction, infant mortality, disease, and inter-troop relationships in troops living at the most arid extreme of the species. Domestic animals, particularly donkeys and goats, are common in and near the lower Kuiseb riverbed. Their changing populations may affect indigenous species, including plants, game, and invertebrates (GABRIEL, 1992; ZEIDLER, 1995). Outside the Kuiseb catchment, there are numerous other studies of Namib mammals that are continued or repeated on a long-term basis, including in communal areas. An example involving DRFN is LEGGETT's (1998, 2000) and Save the Rhino Trust's extension of elephant monitoring previously conducted by VILJOEN (1988).

Invertebrates and small vertebrates – A major contribution to the long-term account of Namib Desert animal populations is the intensive pit-trapping programme of DRFN. Although it focuses primarily on the monitoring of Tenebrionid beetles as "key organisms", it also provides a model for other desert organisms. The concepts that are derived in this study underpin many biodiversity studies undertaken in hyper-arid and arid environments, specifically Namibia. Because of its significance, the tenebrionid long-term research will be dealt with in some detail below. However, the long-term pit-trapping programme is also monitoring many other animals besides tenebrionids in the Namib, e.g. other beetles, solifugids, and lizards. The repeated monitoring technique has been used for the lizard *Meroles anchietae* (ROBINSON, 1990; MUTH, pers.comm.), golden mole *Eremitalpa granti* (FIELDEN, 1989; SEYMOUR and SEELY, 1996) and gerbils (DICKMAN, pers.comm.). These small vertebrates appear to track long-term trends in rainfall. Ants (MARSH, 1986) and soil microarthropods (ANDRÉ *et al.*, 1997) are also good candidates for repeated monitoring due to their importance. Annual monitoring of three spider species since 1987 is revealing how their populations relate to different aspects of the environment, namely food (mainly tenebrionids and ants), and substrate instability, e.g., due to sand storms or trampling by ungulates. Long-term monitoring and modelling demonstrate how these factors affect clusters of spiders and how clusters develop, shift, and decline over generations (HENSCHEL, 1990, 1995; HENSCHEL and LUBIN, 1992; EISINGER *et al.*, 1998; HENSCHEL, 1997). Such work also serves as a model for other animal populations surviving in extreme and variable environments. These invertebrates and small vertebrates provide substance to several kinds of field ecology courses at Gobabeb.

At the DRFN research sites in the farming areas in southern Kunene region pit-trapping studies of tenebrionid beetles (see below) as well as monitoring of biodiversity of abundant representatives of the soil fauna, namely termites (Isoptera), were recently established. Working over most of Namibia, ZEIDLER (1997) analysed termite communities throughout Namibia 30 years after COATON and SHEASBY (1972) had done so. Further current studies are directed at elucidating some underlying reasons for differences in termite communities, such as changes in rainfall and land use patterns (e.g. ZEIDLER, 1999). The biodiversity measures of the termites are related to the soil processes and resources affected by them.

Tenebrionid Beetles – The long-term pit-trapping project that focuses on tenebrionid beetles (Coleoptera) in the Namib serves as an example of the DRFN marrying findings from Namib-LTER with case studies in farming-LTERs. Tenebrionids are good indicators of environmental conditions because their populations integrate several environmental factors, namely, detritus, leaves and dung on which they feed, vegetation cover under which they shelter, the hardness, moisture and stability of the soil, and the availability of water from rain, fog, and runoff. Furthermore, tenebrionids are abundant, conspicuous, diverse, flightless, and easy to capture and identify. Taxonomic, ecological, behavioural and ecophysiological studies have devoted much attention to Namib Tenebrionidae (more than 180 published papers). These factors make these beetles excellent subjects for further in-depth research and for environmental education.

In an ongoing study initiated in 1968, we are investigating the long-term population dynamics and the species composition of tenebrionid beetles in six habitats near Gobabeb, namely the Kuiseb riverbed, gravel plains, the interdune plains, dune hummocks, dune slope and dune slipface (HENSCHEL, 1994; HENSCHEL, SEELY and POLIS, 1998). Pit traps are operated at weekly to bimonthly intervals. Various diversity indices are derived from the pit trap data and population trends are revealed by comparing the time sequences of abundance data for each species. Different population trends (increasing / decreasing, rapid / slow, abundant / rare / absent) characterise changes in species composition and diversity. Possible causal factors, such as climate, community interactions, habitat characteristics, and periodicity are examined by correlation and autocorrelation.

The extraordinary high diversity of Namib tenebrionids (total >200) has attracted much attention (e.g., KOCH, 1950, 1962; ENDRÖDY-YOUNGA, 1982; PENRITH, 1986; IRISH, 1990; HENSCHEL, SEELY and POLIS, 1998). Most of the 82 species found near Gobabeb are endemic to the Namib. To date, we have live-trapped 460 000 tenebrionids in the 24-year study period since the studies of LOUW and SEELY (1980), WHARTON and SEELY (1982) and SEELY (unpubl.) initiated the project. We found that abundance is highest in those habitats where detritus is richest (riverbed and slipface), while diversity is relatively high in the habitat where food resources fluctuated most strongly (gravel plains). The time series for various species at first appear to be chaotic (e.g., Fig.2) and difficult to interpret (ZHOU *et al.*, 1997), but some patterns emerge upon closer examination (WOLDA, 1978; THOMAS, 1996). Many of these patterns seem to be related to water availability. Rainfall, fog and river floods appear to be important for population growth of most (but not all) Namib tenebrionid species, but the species differed in the type of water source to which they responded as well as in response rate ("response" being defined as an annual increase in population) (e.g., Fig.2). Population decline after growth also differed between species. These differences may explain coexistence of so many species that use a common food source.

We found that during the years between effective rainfalls at Gobabeb (enough to enable plants to germinate and to produce seeds), Namib tenebrionid populations underwent substantial decline (e.g., Fig. 1). Only few small areas appeared to remain relatively rich in species and biomass. By placing pit traps in and next to these rich patches, we are gaining knowledge of their dynamics (e.g., what factors affect their richness) and how these areas relate to other rich areas (metapopulations) and to poor areas between the rich patches. By examining long-term changes we endeavour to improve our understanding of biodiversity and other ecological processes and to improve the management of source areas. Consequently, the Namib tenebrionid LTER includes areas that can be compared as possible sources and sinks, such as dune slopes (near Kahani 23°39'S; 15°01'E and at Khommabes located 10 km SW and 10 km W of Gobabeb respectively) with different quantities of perennial vegetation such as hummocks of the grass, *Stipagrostis sabulicola*, and !nara, *Acanthosicyos horridus*.

The long-term data series on tenebrionid populations demonstrate how LTER can form a valuable backdrop to the interpretation of short-term studies (Fig. 2). Beetle community composition appeared to differ in relation to food, soil, vegetation cover, water availability and climatic variability. Some of these factors are susceptible to local change by people, and this forms part of the study at Olifantputs. There we are examining how potential source areas of tenebrionids and termites (e.g., areas where land use by livestock is light) can serve as potential areas to recolonise disturbed areas (e.g., areas heavily grazed and trampled by livestock). This demonstrates one way by which the knowledge gained in the Namib LTER can be applied in communal farming areas such as Olifantputs (PARENZEE, 2000). Here, pit trapping and other monitoring research activities of tenebrionid and termite biodiversity have been initiated to investigate these organisms' potential as indicators of biological integrity at sites with different levels of land use intensity (BARNARD *et al.*, 1999; PARENZEE *et al.*, 2000; ZEIDLER *et al.*, 2000).

People and Livestock

Livestock – At the farming LTER sites the monitoring of domestic animals plays a particularly important role. In order to establish land use histories and long-term records of land use intensity, livestock and domestic animal demographics need to be constructed (ZEIDLER, 1999). In the past the agricultural extension officers have been collecting data which are integrated into the DRFN databases that include our current data and information on historic trends obtained from the rural community members, e.g. by Participatory or Rapid Rural Appraisal (PRA and RRA) methods (ZEIDLER, 1999). The data set should also incorporate data on fodder subsidies during periods of drought ("drought relief") and their effects on the numbers of livestock that are being kept beyond the numbers that can be sustained by the natural grazing available (HENSCHEL, 1996).

People – Long-term data on rural populations assist the interpretation of the interactions of people with the natural environment and the management of natural resources. At the NAPCOD study sites in southern Kunene region baseline data on human demography have been recorded using PRA and RRA methods (ZEIDLER, 1999). Long-term records include human demography and the use of natural resources, e.g. borehole water and grazing. Information on village populations and migration patterns to emergency grazing areas are being incorporated into this monitoring programme. This information is being compared to our concurrent data on environmental indicators, such as vegetation, termites, tenebrionids and soil characteristics. The latter, in turn, is compared to the Namib LTER data. A similar approach is being used to monitor natural resource management by the Topnaar community along the Kuiseb River, particularly concerning !Nara, water and livestock (BOTELLE and KOWALSKI, 1995; HENSCHEL, MTULENI *et al.*, 1998; SHILOMBOLENI, 1998; BÜTTENDORF and HENSCHEL, 1999; AMOOMO *et al.*, 2000).

Using and Applying LTER Data

Various examples of how DRFN is using, combining and applying LTER were given throughout the paper. This section describes the general research process of the DRFN as well as the outputs that are geared towards increasing the awareness and understanding of arid lands, including its biodiversity (see also SEELY *et al.*, submitted).

First, many short term research results, particularly those that feature aspects of biodiversity in arid environments, can be interpreted against the background of long-term trends. This is of great value for studies conducted throughout arid Namibia, but also when looking at arid land ecology world-wide.

Second, it is a policy of the DRFN to make its LTER data available under given conditions (DRFN, 2000). LTER data are housed in a central place, advertised and made accessible for further use. Sharing of data is of fundamental importance for involvement with collaborators, including the Na-LTER and ILTER networks (Na-LTER, 2000).

Third, data and tested methods of the Gobabeb LTER serves as baseline or comparative information for many other studies and applied programmes in arid and semi-arid parts of Namibia. Some examples were given above in relation to NAPCOD. Further examples relating to the goal of reducing people's vulnerability to loss of sustainable livelihoods in variable environments relate to characterising the state of the environment and identifying vulnerability (e.g., QUAN *et al.*, 1994; SEELY and JACOBSON, 1994; BEHNKE and SCOONES, 1992; JACOBSON, 1997b; WARD and NGAIRORUE, in press). The characterisation through LTER of natural variability is crucial for distinguishing apparent from real environmental changes (e.g., SULLIVAN and KONSTANT, 1997; ROHDE, 1997a; SULLIVAN, 1998, 1999; WARD *et al.*, 1998). Furthermore, LTER provides details of mechanisms underlying long-term changes identified, for example, in archaeological studies (e.g., SANDELOWSKY, 1976; KINAHAN, 1991; SCOTT, 1995) and palaeoclimatology (e.g., HEINE, 1998; LANCASTER, 1998). In this way, LTER effectively complements other research fields concerned with characterising environmental changes.

Fourth, information available is incorporated into text books on desert ecology, resource materials for school teachers, natural history overviews, nature films, coffee table books, and information packages for resource managers and policy makers (described by SEELY *et al.*, this volume, submitted).

Fifth, national resource management schemes and policy-making projects require long-term data. Prominent among these in Namibia the Framework Convention on Climate Change (FCCC), the Convention of Biological Diversity (CBD) and the Convention to Combat Desertification (CCD), and the National Drought Policy. State of the Environment Reports and formal Workshops serve to provide feedback from Namibian and international forums (SEELY *et al.*, submitted).

Sixth, the most important point, all DRFN research is connected to an explicit training component involving students as well as natural resource users and managers in the collection and interpretation of the data. Such a participatory research process contributes to the capacity building of natural resource users and managers. Rural resource users are directly involved in research on natural resources so that they themselves can provide effective feedback towards conclusions. This facilitates devising nation-wide mechanisms for sustainable resource management and environmental monitoring. The NAPCOD programme serves as leading example of this connection.

General Discussion

Biodiversity reflects a combination of environmental and historical events at a site and changes in biodiversity can provide a sensitive measure of ecologically relevant changes in the environment. LTER can provide historical data, while allied studies focus on the proximate relationship between organisms (including people) and the environment (RISSER, 1995; BARNARD, 1998a).

The Gobabeb and other LTER sites described here are part of a larger network of LTER sites concerning arid lands. Prominent among these are further NAPCOD sites that include old SARDEP sites, the Kalahari Transect covering parts of South Africa, Namibia, Botswana and Zambia (SCHOLES and PARSONS, 1997), the planned BIOTA African Transcontinental Transect (JÜRGENS, pers.comm.) and transects covering other deserts of the world (KOCH *et al.*, 1995). These and other initiatives are interconnected via the Na-LTER network (Na-LTER, 2000) and through collaboration along several other avenues. It is anticipated that a regional SADC network of LTER sites may arise within the ILTER network (ILTER, 1999) and that the Na-LTER sites will contribute to these.

Continuity and consistency in methods are required for LTER. However, LTER should be more than generating and interpreting data and it ultimately needs to involve human communities. The Gobabeb LTER projects demonstrate that baseline information and understanding derived from an undisturbed, arid environment is invaluable to the interpretation of shorter-term data collected in other arid areas. This should ultimately enable brief assessments of biodiversity to be used to describe habitat quality. Likewise, it allows an interpretation of the effects of people on biodiversity and facilitates the planning of projects in populated areas that may change these effects.

Biophysical and socio-economic LTER projects are extremely important for the Namibian environment. This has long been recognised by several other organisations besides the DRFN, e.g. the Ministry of Agriculture, Water and Rural Development, and the Ministry of Environment and Tourism, as well as other NGO's like the Save the Rhino Trust (over 20 institutions have thus far declared interest in Na-LTER). However, today it becomes more and more difficult to maintain long-term sites. There appear to be several reasons. First, the maintenance of long-term environmental research is costly and demands much dedication. Second, the value of long-term data collection is often not fully recognised. This may partly be because LTER data and conclusions are sometimes not published appropriately and timely nor made accessible. The current paper demonstrates the value of published LTER data for many social and environmental fields in Namibia.

Conclusions

In this paper we show how LTER has developed at Gobabeb since Independence, including generating, sharing, understanding, using and applying research results for training and management purposes. LTER is important for arid land studies. Its ultimate value depends on the alliance between basic research and applied research that underlines the importance of both. In the long run both types of research cannot do without each other. Basic research is vital because it provides first-hand knowledge that can be translated and applied into relevant information to relevant target groups. Basic research often comes up with novel insights that were not initially predicted. Knowledge can in this way advance in quantum leaps. However, without its application, basic research can develop into an ivory-tower condition that a developing country can ill afford. It is the fruitful interaction between basic and applied research that increase the value of both. Well-tested conclusions and honed skills can be transferred from basic to applied research, while applied questions form a guiding framework for basic research. LTER embraces both.

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