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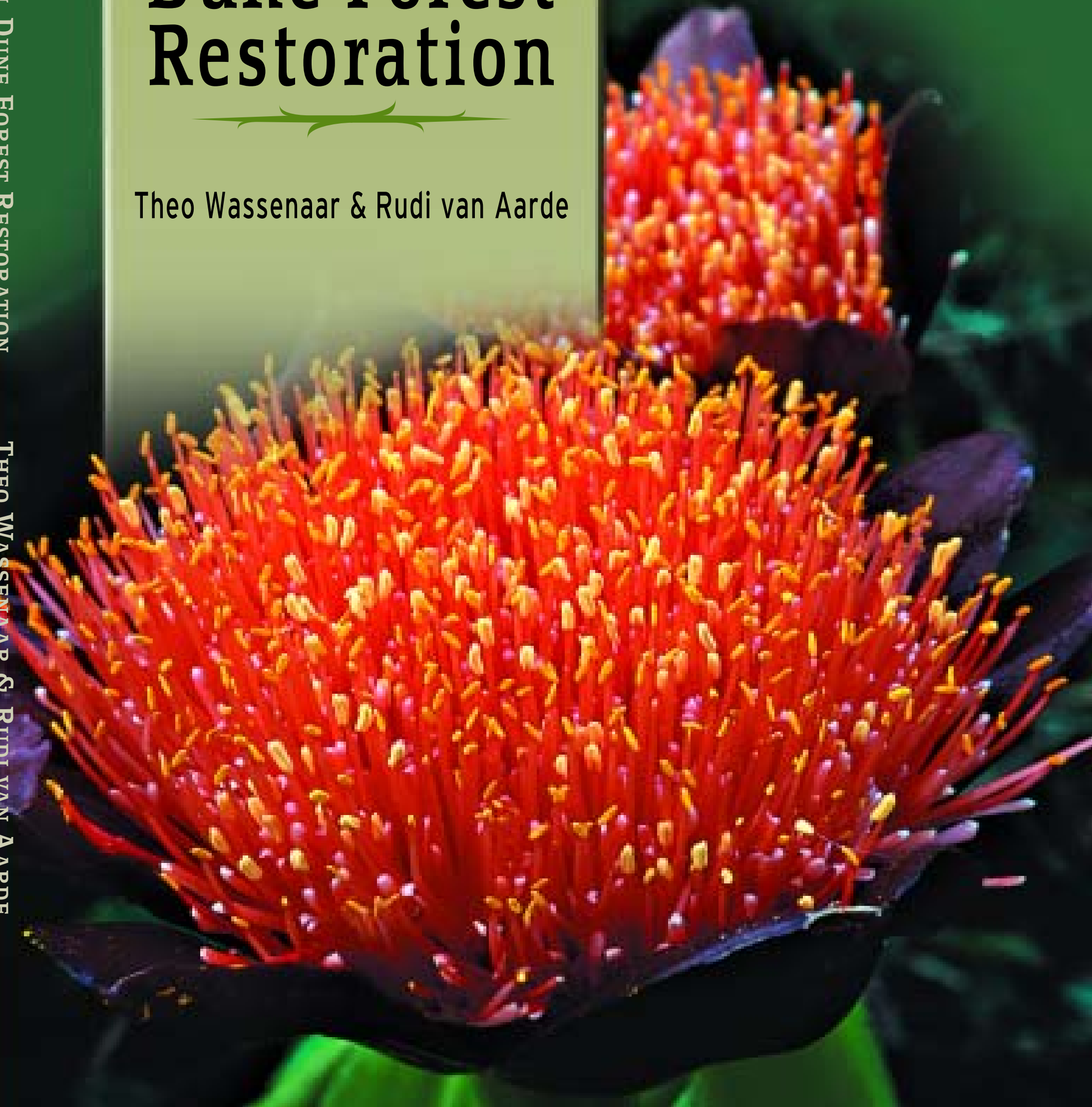

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Published - February 2005

Design and layout: Loretta Steyn Graphic Design Studio - Pretoria

Printed by: Ultra Litho - Johannesburg

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Introduction

Humanity entered the new millennium with one of the greatest challenges it has ever faced. It has to ensure that future generations will have the same natural resources at their disposal that we (and those before us) have had available to us. South Africa's commitment to the sustainable use of natural resources flows from our Constitution, which enshrines the right of present and future generations to live in a healthy environment. But a healthy environment is more than just clean air and water; it is an environment that can sustainably support life. It doesn't appear from nowhere, nor can it be achieved or maintained by merely cleaning up the rubbish from our rivers and our air – a healthy environment is created and driven by intact, healthy ecosystems and natural processes.

This is more than a conceptual emphasis. It implies that BIOLOGICAL DIVERSITY (see glossary) is the real engine of a life-sustaining environment. The protection of biodiversity therefore benefits humankind directly. Sustainable living thus includes biodiversity conservation, an activity that can no longer be limited to fenced-off protected areas, or considered the responsibility of uniformed conservation managers. In fact, most biodiversity still occurs and operates beyond the boundaries of protected areas. Sustainable living thus can contribute a great deal to conservation.

Key questions

- ***What is sustainability and how does it relate to biodiversity conservation and restoration?***
- ***How does RBM apply this concept?***
- ***What is this booklet about?***

Globally, about 12 percent of land area has been set aside for conservation. Because species diversity is so intimately linked to the amount of available land area, in simple terms this means that in the long run we stand to lose about 80 percent of all species. This ecological perspective of earth is unfortunately far removed from the day-to-day realities of human social and economic issues. For generations we have concentrated on social and economic development, neglecting to set aside enough land for the conservation of biological diversity. Consequently, today's generation is saddled with far greater conservation problems and more conservation responsibilities than any before them.

The need to increase conservation efforts is clear, particularly in ecosystems such as forests, where a large portion of biological diversity is concentrated. But how do we solve this conservation problem? At first glance an increase in the amount of formally protected land is an obvious possibility. But land is scarce. Most land outside current protected areas is set aside for some form of economic activity (e.g. agriculture, mining, cities) and has hence become expensive. And there is a more basic issue as well – these land-uses do not have a conservation focus and often leave the land ecologically degraded. In the end, biodiversity conservation is left with few options and is being squeezed into ever more isolated, fenced enclaves.

However, the last two decades have shown that abandoned agricultural and industrial land may be conservation's largest missed opportunity, because degraded land can be restored to its former biological state. The principles of ECOLOGICAL RESTORATION (see glossary) are applied across a wide range of human-disturbed areas, however, the techniques have been refined in the rehabilitation of abandoned mines. It has grown from being little more than glorified gardening into a range of sophisticated management activities based on ecological concepts such as disturbance, succession, metapopulation dynamics, and the ecology of colonization. Ecological restoration, and RESTORATION ECOLOGY, lies at a unique point between ecological theory and its application in the real world. It is therefore often referred to as an "acid test" for our knowledge of ecology – if we really know what makes ecosystems tick, we should be able to put a broken one back together again.

To the extent that it is possible to repair human damage to an ecosystem (and we will show that it is), ecological restoration thus has a definite and strictly utilitarian conservation value. However, ecological restoration is about more than the mechanics behind the recovery of ecological STRUCTURE and FUNCTION, it has a direct philosophical link to the concept of sustainable living. Indeed, because it is concerned with the restoration of ecosystem integrity (the basis of all life), ecological restoration can perhaps be seen as the most fundamental application of sustainability.

The mining company Richards Bay Minerals (RBM) supports social and environmental activities that go hand in hand with the protection of biological diversity. Mining, by its very nature, destroys biological diversity. And mining in a biologically unique area of global conservation significance, the Maputaland Centre of Endemism (Box 1), puts the potential damaging effects of mining and the consequent challenge to lessen their impact into

BOX 1

Maputaland – a jewel of biological diversity

Maputaland (the lighter area in the map on the right) is a vast area straddling the border between South Africa and Mozambique. It is biologically exceptional in the diversity of plants and animals it supports (more than 2500 plant species), and in the high number of these species that occur nowhere else on earth (almost 10% of the plant species are endemic).

Maputaland's name derives from that of the Tonga Chief Mabhudu, who lived south of Delagoa Bay (now the city of Maputo) in southern Mozambique, and the area is still inhabited by the Tonga people. Much of the peculiarly high diversity and endemicity of Maputaland is associated with two remarkable vegetation types: sand forest (a dry tropical forest, found mostly on the ancient dune ridges of the coastal plain) and woody grassland (a type of grassland characterized by abundant dwarf woody plants with underground stems, like buried trees). But the sub-tropical forests of the first dune cordon, a distinct ecotype in Maputaland, are remarkable in their own right.

Maputaland lies at the southern end of the African tropics, with very few floristic links to the Cape or Afromontane regions. On the other hand, it does share many floristic elements with tropical east and central Africa (connecting it to the Zanzibar-Inhambane and Somalia-Masai Floristic Regions), with many of these forest plant and animal species reaching their southernmost distribution here. The dune forests can therefore be seen as a route that connects the forests of southern Africa, and particularly South Africa, with those of the rest of tropical Africa.

Maputaland has few parallels. It must be conserved, both for our own sake, and that of future generations. RBM's efforts to restore dune forests in part of their natural range is going a long way towards ensuring the maintenance of the species and ecological processes that underlie the integrity of the dune forest ecoregion of Maputaland.

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BOX 2

The Rio Tinto Biodiversity Strategy Position Statement

"Rio Tinto recognises the importance of the conservation and responsible management of biological diversity as a business and societal issue, and aims to have a net positive impact on biodiversity.

Rio Tinto will integrate biodiversity conservation considerations into environmental and social decisions and actions in the search for the sustainable development outcomes to which Rio Tinto is committed. In some cases this will mean that projects may not proceed.

Rio Tinto seeks a position of leadership and influence in the mining industry on biodiversity issues. We believe that recognition of that position and of our performance on biodiversity issues will create benefits for our business.

We are committed to:

- ***the prevention, minimisation and mitigation of biodiversity risks throughout the business cycle;***
- ***responsible stewardship of the land we manage;***
- ***the identification and pursuit of biodiversity conservation opportunities, and;***
- ***the involvement of communities and other constituencies in our management of biodiversity issues."***

Extracted from www.riotinto.com

stark perspective. For RBM a commitment to the sustainable use of resources, in line with Rio Tinto's biodiversity strategy (Box 2), therefore requires the restoration of lost biological diversity. For some 27 years RBM has been mining the coastal sand dunes of northern KwaZulu-Natal for the valuable minerals such as ilmenite and rutile (Box 3). The concurrent post-mining REHABILITATION of coastal dune forest, driven by ecological processes, has shaped degraded dune forests in the mining lease areas into a series of dune vegetation stages. RBM's objective is to restore the biological diversity typical of a coastal dune forest. This implies that the company relies on natural ecological processes to regain species diversity and the processes that revolve around their persistence. Such a long-term commitment to ecological restoration,

BIOFACT

COMMUNITY: *Community is an operational term, closely related to "assemblage" (and used interchangeably), and refers to any group of species that have similar properties (such as a community of plants, or of rodents or millipedes). The meaning is entirely context-dependent; in one study a community of plants may for instance refer to all plant species in a forest, while in another the term might refer only to trees while excluding woody shrubs on the forest floor.*

BOX 3

Mining the sand dunes of KwaZulu-Natal

In 1791 William Gregor, an amateur chemist, extracted a "black sand" (ilmenite) from a river using a magnet. By treating it with hydrochloric and sulphuric acid, he produced the impure oxide of a new element, later named titanium by the German chemist Klaproth. In the days of Shaka Zulu the minerals in the "black sands" of this region were used to make iron weapons, but it is likely that these minerals were used even earlier than that.

Ilmenite, rutile and zircon are common minerals, found all over the world, but often not in economic concentrations. The coastal area of northern KwaZulu-Natal along the Zululand coast is one of the exceptions. The minerals here originate inland, from rocks that are eroded over aeons. These erosion products are washed down the Umfolozi River into the sea, from where it is deposited in the high dune ridges of the coast.

RBM uses an ingenious dredge mining operation, pioneered in Holland and Australia, to extract and separate ilmenite, rutile and zircon (about 5% in volume) from the dune sand. To do this an artificial freshwater pond is created in the dunes, on which the dredger and concentrator plant float. Burrowing into the mining face of the dune, the dredger advances at a rate of 2 to 3 metres per day, depending on the height of the dune. As the sand face is undermined it collapses into the pond, forming a slurry that is sucked up and pumped to a floating concentrator. Here the heavy minerals are separated from the sand using a gravity process, and then stockpiled as heavy mineral concentrate. At the mineral separation plant the ilmenite is removed by successive stages of low and high intensity magnets, and the non-magnetic materials (zircon and rutile) are separated using an electrostatic process.

Zircon and rutile are sold in their raw form as mineral sands, but ilmenite is first turned into titanium dioxide slag and iron in an electric smelting process. Titanium dioxide slag is crushed and classified according to particle size and sold largely to pigment manufacturers. The iron is further purified and alloyed before being sold. Only 5% of RBM's production is used in South Africa, the rest (almost two million tons) is exported. The company supplies about a quarter of the world's pigment and welding rod market, a quarter of the iron for ductile iron castings, and a quarter of the world's zircon. Ilmenite, rutile and zircon are used to manufacture of a variety of products that are essential to our modern lifestyle.

Titanium dioxide reflects and scatters light in the visible spectrum like thousands of tiny mirrors, making it an essential element of bright pigments in paints, plastics or paper. It is also used in toothpaste and in modern sunscreens because it absorbs ultra violet (UV) rays from the sun and is non-toxic. Rutile is mainly used in welding rod fluxes (it stabilises the arc and protects the molten metal from oxidation during welding, forming a superior welding joint), and in producing titanium metal. High purity pig iron is used as a raw material in foundries for the production of ductile iron castings (a strong, castable metal used for the production of safety- critical automotive parts, such as brake callipers and steering knuckles in cars). Zircon has a very high melting point and is therefore extensively used in the production of ceramic tiles and sanitary ware, and in foundries.

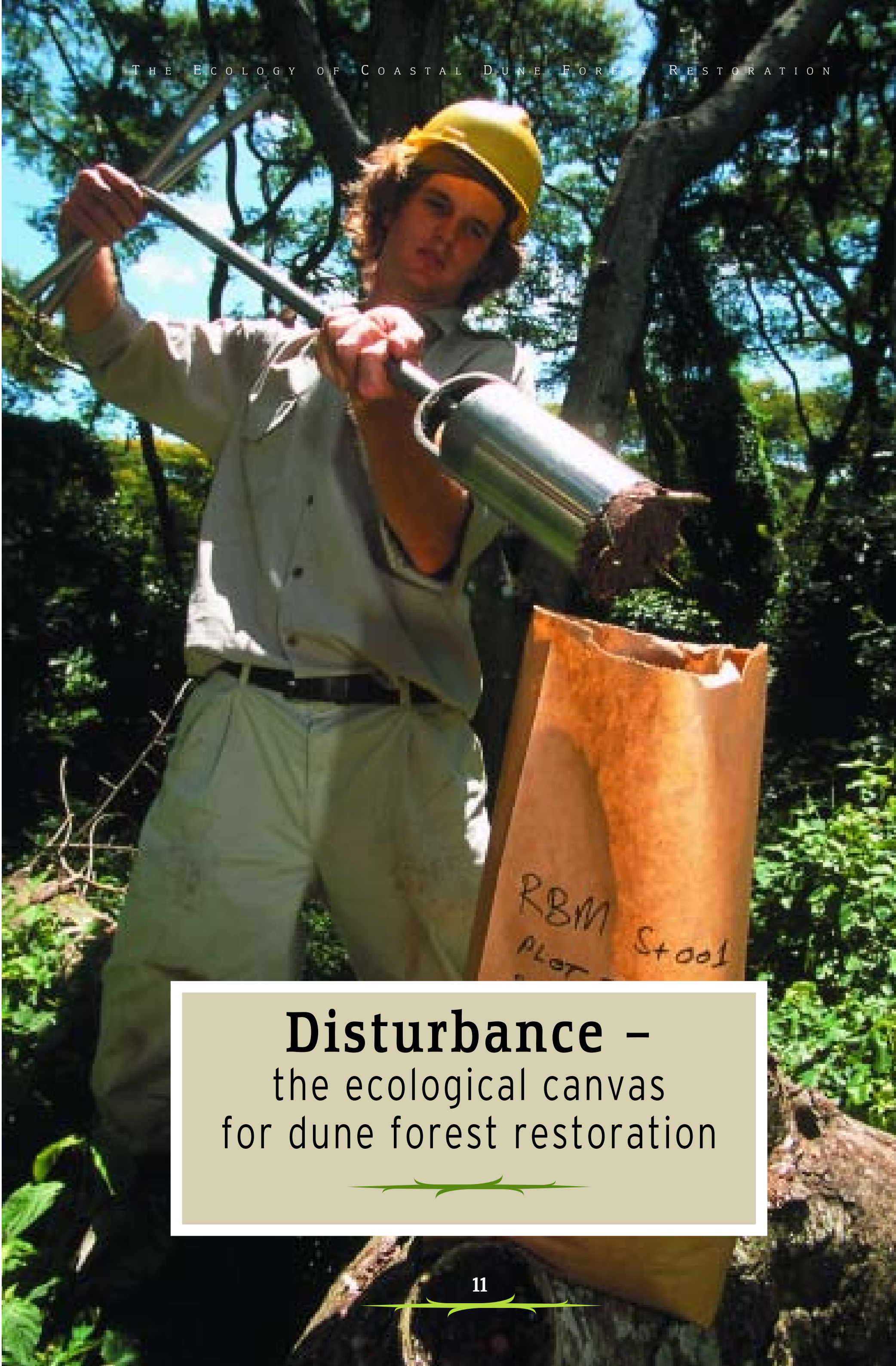
Titania slag and pig iron are the bulk of the business and the process whereby ilmenite is beneficiated ensures RBM'S place as a world-leading producer. The combined output of the four furnaces at RBM is some one million tons of slag and 525,000 tons of iron per year.

Extracted from www.rbm.co.za

specifically using natural processes, is unique in South Africa and puts RBM at the forefront of this activity in Africa.

To achieve its goal, the company committed itself to an independent scientific research program that both evaluates their restoration effort according to set ecological criteria, and guides their restoration management decisions. This has set the stage for the design of a series of ongoing studies that deal with the regeneration of coastal dune forest community COMPOSITION, structure and function. These studies are guided by the principles of academic independence and freedom, as well as being conducted within the framework of modern scientific practices.

In this booklet we describe the ecological background of ecosystem recovery (the ecology of disturbance and succession), and the monitoring and supporting research programs that we designed around it. We also summarise the findings from the large number of studies that have been conducted on several biological groups over the last 13 years. But research should not only describe and analyse, it should also lead to improved restoration practice. We therefore describe our thinking behind the principles and theory of restoration ecology, and how this can be put into practice in a mechanistic research framework that will inform management decisions directly.



Disturbance – the ecological canvas for dune forest restoration

Perhaps more than others, Africans know that Nature can be capricious and erratic. Droughts, floods, fires, and many other agents disturb the natural "balance", to the point that the only balance that ever seems to be achieved is that of continuous change. But this is not necessarily a bad thing – disturbances are very often a prerequisite to overcoming the competition for resources between species, and are hence seen as one of the primary reasons why many organisms can coexist. Disturbance is thus a part of the natural ecological landscape, and strip-mining, although disturbing nature in a more ruthless manner than what a drought can, is essentially just another form of disturbance.

Key questions

- ***What is the ecological context of disturbance?***
- ***What happens after a disturbance in nature?***
- ***How can the management of ecological restoration utilise natural response mechanisms?***

Nature has an inbuilt response to disturbances – after a disturbance, the previous collection of organisms is "re-assembled" through a complicated process of ecological succession. This is vital for the practice of ecological restoration. The response of an ecosystem to a disturbance is dictated not by the agent responsible for the disturbance, but by the degree and severity of it. For an ecological restoration manager this means that it is often possible to use the inherent response mechanisms of ecological communities to restore a particular ecosystem after it has been disturbed.

There are exceptions. For instance, in some ecosystems the changed post-disturbance conditions prevent re-colonization by a particularly important species or set of species. This is often enough to switch the whole ecosystem's trajectory away from recovery and

BIOFACT

SUCCESSION: *Succession is a directional development in the species composition of a community after a disturbance, from so-called pioneer stages, to an end-state that tends to persist. Early ecologists viewed the process of succession almost like an organism that develops deterministically from an embryo (the "pioneer" stage) to a mature individual (the so-called "climax" stage). We now know that this classic emphasis on deterministic changes over time and on a stable and predetermined endpoint is wrong. There are in fact many possible persistent species compositions for the end-state, and many pathways to get there. The pattern of changes in species composition (what is observed as succession), and the end-stage composition (the climax), are often similar between disturbances, because the set of factors that influences species colonization and persistence is also often similar.*

into an ALTERNATIVE STATE (see glossary). Often there are also no source populations (populations of species on an adjacent undisturbed habitat that can provide dispersing individuals) left in the immediate vicinity and drastic actions, such as large-scale species re-introductions, have to be taken. Many human-induced disturbances result in toxic chemical pollution, allowing only a few, specially adapted species to survive. In these cases, the resources essential for life have been altered to such an extent that no natural process will be able to repair the ecosystem. Full-scale and often ineffective human intervention now becomes necessary for the establishment of viable populations in the disturbed area. Sometimes rehabilitation ecology is therefore geared more towards the mitigation of constraints on the establishment of new populations, than simply managing the process and pattern of COMMUNITY ASSEMBLY.

However, at the other end of this post-disturbance scale, where the substrate is left relatively intact after the disturbance, where changes to the chemical and physical environment are relatively small, and where source populations are available, a restoration manager can use natural processes such as succession to assist in the repair of the damaged ecosystem. The restoration of dune forests at Richards Bay, a relatively mild form of intervention that explicitly utilizes succession, is geared towards this end of the scale. Beyond the provision of topsoil, wind protection and alien plant control, and the introduction of some pioneer plant species, relatively little is done to change resource (soil, air and water) quality or to re-introduce forest species. In this case, the actual re-assembly of the forest community is left mostly in nature's hands.

The mechanics of **forest re-assembly**

During succession groups of plant species, adapted to different environmental conditions (for instance, full sunlight immediately after disturbance, and nearly full shade later as the canopies of the first tree colonists close up), sequentially replace each other until the original climax or end-stage species composition is recovered. But succession is not an entity in itself, it is a symptom of the interplay between two highly mechanistic processes: colonization and extinction. More importantly, and unlike the term "climax" would suggest, it does not have a pre-determined endpoint.

For any disturbed patch of dune forest to recover its former species composition, and hence also its STRUCTURE (see glossary) and FUNCTION, the former complement of forest species must again disperse to the new habitat from surrounding forests, and, once there, must establish reproducing populations (colonization). At the same time, the pioneer species, those species that specialize in colonizing in the harsh, early post-disturbance environment, should decrease in numbers and eventually disappear (local extinction) as conditions become unsuitable for them, or they are outcompeted. Together, local colonization and extinction therefore constitute the mechanics of succession.

Key questions

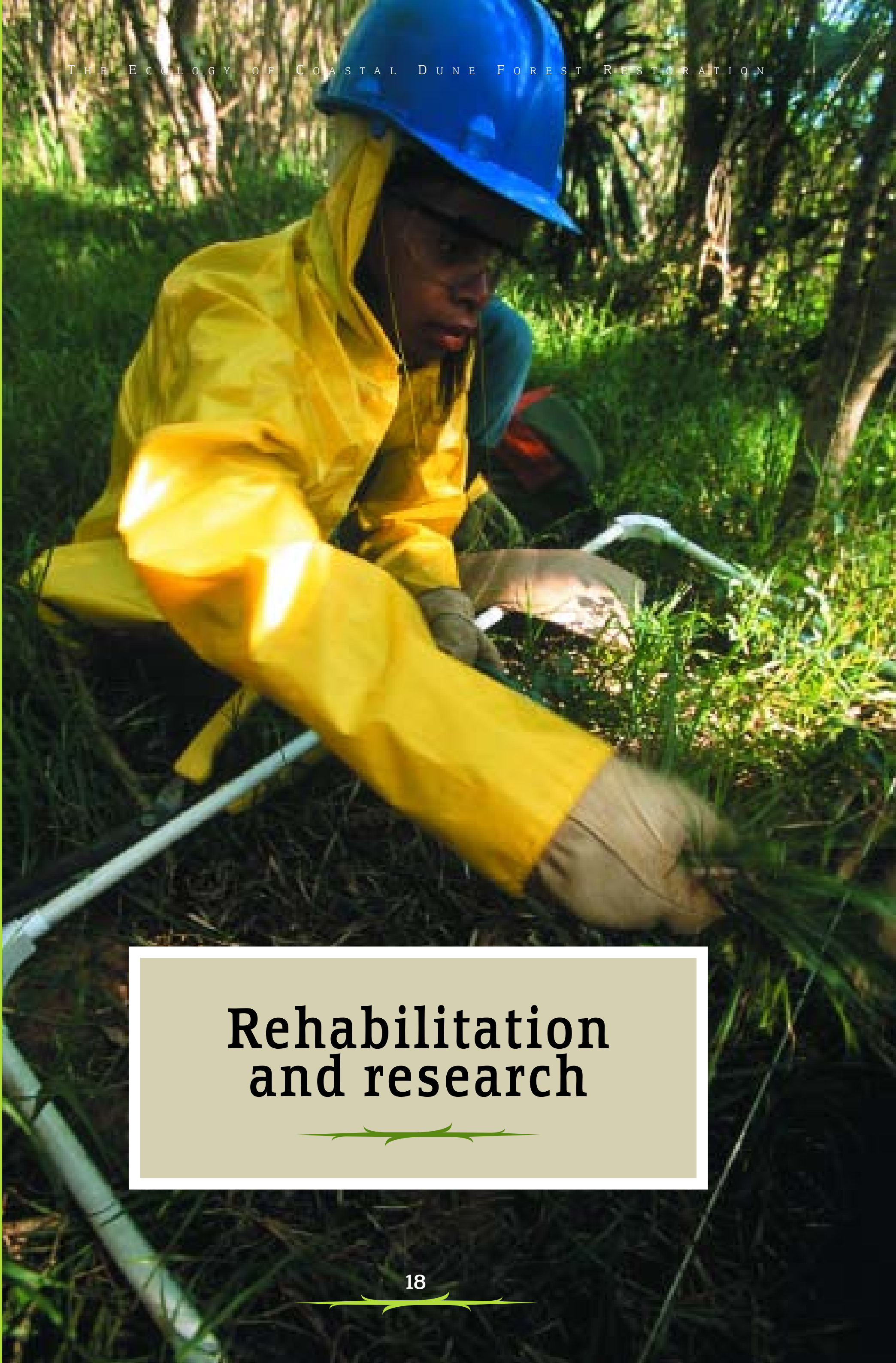
- ***What is community assembly?***
- ***What are the chances of re-assembling a particular community?***
- ***What factors influence the colonization of the new habitats by forest species?***
- ***Can a forest ecosystem be restored?***
- ***What factors will influence the chances of success?***

Successional change occurs in any disturbed forest, regardless of the origin of the disturbance. But a community is not always re-assembled so smoothly. Compromising any part of the dispersal-establishment-extinction chain will push succession off the rails. And there are many reasons to expect that this might happen. For instance, just as the same sequence of numbers is never drawn in two successive Lottos, the rules of chance suggest that multiple combinations of species could be drawn from the pool of available species in any of the surrounding habitat types. Empirical and theoretical studies suggest that this is indeed often the case – for instance, random ordering of species arrivals seems to make a huge difference to the likelihood of finding a particular community composition in models of COMMUNITY ASSEMBLY.

But there are also many practical reasons why this should happen. Sometimes, purely by chance, a particularly competitive species will colonize very early in the sequence and thus prevent other species from doing the same. The outcome of such a skewed successional sequence might look quite different from the original assemblage. More prosaically, many of the potential colonists in the species pool come from other, non-forest ecosystems that might equally claim the new habitat. Furthermore, colonization ability differs between species, because it is not a simple attribute; it consists of the sum total of the probabilities that a species will disperse at the right time, in the right numbers, and find conditions in the new habitat suitable for establishment. Together these factors can lead to much uncertainty about the new community's species composition.

However, nature re-assembles ecosystems quite differently from the way Lotto numbers are drawn. In reality colonization is never a completely random event; the order of invasion is highly constrained by factors such as the distance to source populations that provide dispersing individuals (if they are close, the likelihood of dispersal is good), the presence of dispersing agents such as fruit-eating birds, bats and monkeys, and even the prevailing wind direction. Rather than causing unpredictable outcomes, the factors that constrain and assist dispersal and establishment tend to strongly direct the sequence of events that culminates in a PERSISTENT STATE. Of course, there is always the chance that the sequence of events will be different from the previous time, because the driving factors may have changed. Colonization may, for instance, be prevented at a very basic level – polluted soils may prevent the establishment of most plant species, while excessive distance to a source population may decrease the likelihood that dispersing individuals, plant or animal, may even arrive at the new habitat. However, 13 years of research on dune forest restoration have shown that this is rare in practice – only a few forest assemblages do not recover by 25 years after the disturbance.

So, can we heal the wounds of disturbance? Apparently, yes. The chances are good that if you "play the tape of life again", the same set of driving factors will drive the same sequence of events, and history will repeat itself. But it is also obvious that we need to understand how and when these factors affect the dispersal-establishment-extinction chain if we want to assist the ecosystem recovery process. Knowledge of the mechanics of dune forest regeneration means that we can assist the re-assembly process intelligently – we can focus our attention only on those species that have trouble (more than could be expected in nature) in dispersing to or establishing themselves in the newly created habitat. Or we can focus on those processes that appear to be out of sync with the natural ones. The assisted recovery of ecosystem structure and function is the essence of ecological restoration. Its success clearly depends on a sound scientific understanding of natural regenerative processes.



Rehabilitation and research

The colonization-extinction interaction metaphor provides an easy and intuitive framework, both for the rehabilitation program itself, and for research on the principles and practicalities of ecological restoration. As prescribed by the mining lease agreement, RBM started their indigenous dune forest rehabilitation program in 1977. Fifteen years later RBM also started to support an independent academic research program on the ecology of restoration. The rehabilitation program (see Box 4) takes the common-sense approach of copying the successional process on naturally disturbed coastal dune forests throughout the region.

Key questions

- ***What is the premise of the rehabilitation program?***
- ***What is the premise of the program to monitor ecological development?***
- ***What are the objectives and premises of the ecological research program?***
- ***What is the overall theme of research and monitoring?***

In these disturbed and abandoned patches, the pioneer tree species *Acacia kosiensis* (Swartz) (dune sweet thorn) forms closed woodlands lasting as long as 30 to 50 years. The closed woodland provides, at the same time, safe germination sites for forest plants, and habitat for seed-dispersing mammals and birds. A large fraction of the true forest tree species can therefore invade and establish reproducing populations during the woodland stage, providing further opportunities for dispersal by attracting other dispersers. In this way, the dispersal-establishment-extinction ball starts rolling, and the restoration manager's task is to make sure that it stays on track and keeps on rolling. Essentially, RBM's rehabilitation program achieves this by establishing stands of *A. kosiensis* close to source areas, and then controlling the spread of invasive alien plants.

Twenty-seven years have passed since the start of active REHABILITATION (see glossary) in 1977. Since then, a part of the mined area has been rehabilitated every year. This continuous addition of new regenerating sites over such a long period has led to the development of an ideal outdoor laboratory for research; a place where we can study how dune forest plant- and animal COMMUNITIES are re-assembled after a disturbance, whether these re-assembly patterns conform to current ecological thinking (or not), and how we can best assist the recovery process.

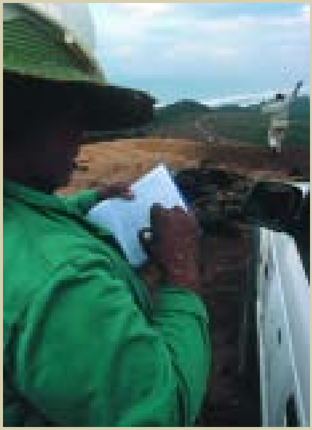
BOX 4

The rehabilitation program of Richards Bay Minerals

RBM's REHABILITATION and REVEGETATION programs are directed by the mining lease contract. Consequently, only one third of the mined area is restored to dune forest (rehabilitation). On the remaining two thirds, RBM is required to establish beefwood (Casuarina equisetifolia) plantations for the development of a charcoal industry (this is revegetation). The 1:2 split is based on the distribution of dune forest and plantations that existed at the time that mining commenced.

Mining leaves bare sand dunes stripped of life and minerals. These sand tailings, shaped to approximately their pre-mining topography, are the templates for the natural development of dune forests. The target is the establishment of a functional, sustainable dune forest, no different to those that typically exist across the region. The first step in this rehabilitation process is to supply the substrate. Topsoil, collected after clearing vegetation ahead of mining, is spread over the bare sand in a thin layer and secured by erecting windbreaks. Annual grass and herbaceous species, some of which have been sowed in, rapidly germinate and stabilise the soil, preventing it from blowing away in the incessant coastal winds.

Within a few months, thousands of seeds of the dune pioneer Acacia kosiensis (dune sweet thorn) germinate, turning the grass and herb covered landscape into a thorny scrubland. This new landscape then develops through several phases that are primarily shaped by the dune sweet thorn. Within 20 years the sweet thorns reach heights of 12 to 15 meters, and over that same period, through a process of self-thinning, their numbers decline from about 15 000 to fewer than 250 trees per hectare. During this period a variety of other plants and animals colonise these newly formed habitats by themselves. When dune sweet thorn numbers decrease to levels below a critical value, gaps start appearing in the woodland. These gaps represent the next phase in coastal forest development and a variety of broad-leaved forest trees now have the opportunity to fill the gaps and provide new habitats to new sets of plant and animal species.



(Left) An aerial photograph of a section of the mining and rehabilitation areas. The mining pond, with a floating dredger and mineral separation plant, is visible in the lower left-hand corner of the picture. Part of the area that has been revegetated with beefwood (Casuarina equisetifolia) is outlined in red, while the two oldest indigenous rehabilitating areas are outlined with green. According to the mining lease contract, beefwood receives the lion's share of the area (roughly two thirds). The remaining third is rehabilitated with the aim of recovering a typical dune forest. The area on the seaward side of the green rehabilitating area is an unmined section of dune forest (interspersed with lines of beefwood, planted almost half a century ago to stabilise dune sand) that serves as a first-line source area for colonizing dune forest species.

Some of the oldest rehabilitation sites have now reached this stage of ecological succession. The coming years, when the woodland has to develop into a fully-fledged coastal dune forest, will provide critical insights into dune mining as an ecologically sustainable exercise. Unforeseen disruptions in the development of these forests through man-induced disturbances may alter the pathway of development and influence regeneration. In addition, the increasing distances between unmined source areas and mined regenerating areas may have consequences for the future development of the dune forests. All of these uncertainties can perhaps best be dealt with through continued research and monitoring. The monitoring and supporting research programs are therefore integral components of RBM's rehabilitation program, because it is the only way to be ensured of continued success.

The basis of our activities is the scientific monitoring and evaluation of the ecological development of regenerating dune forests (Box 5). Because rehabilitation actions simply kick-start what could be a very complex process (the regeneration of community structure and function), it is essential to monitor how the character of the new community changes as it grows older. If nothing else, the patterns of change in the identity of species that are present each year, and in soil properties, should tell us whether the development of our regenerating area is on track.

Our Ecological Monitoring Program (EcolMP) surveys a number of forest species assemblages on all the post-mining regenerating sites, on a number of naturally disturbed regenerating areas, and on several undisturbed dune forests in the region. These undisturbed dune forests are the benchmarks, or reference sites, and provide snapshots of what a restored dune forest should look like, and a tangible restoration target. The objectives, principles and practice of the monitoring program are presented in Box 4.

By monitoring changes in regenerating assemblages, both across time (sequential surveys), and across age (in different-aged sites), we have learnt how dune forests are re-assembled. We also know much about the structure of dune forest assemblages in undisturbed forests, and about how these change through time. But monitoring provides only a picture of the where and what of regeneration.

BOX 5

The ecological monitoring program and its supporting research program

After mining, RBM rehabilitates the dunes by spreading topsoil on re-formed dunes, establishing pioneer plants, and controlling secondary disturbances (such as invasion by alien species, fire, and grazing by domestic livestock). Their objective is the restoration of a typical dune forest, and they harness the natural process of ecological succession to do this. Essentially, RBM launches the ecosystem on a trajectory towards a typical dune forest, a developmental path that is induced and maintained by the same factors that determine development after any other form of disturbance.

The Ecological Monitoring Program (EcoIMP), and the Ecological Restoration Research Program (ERRP), are there to obtain information on the way the ecosystem develops, and on the factors that affect the direction of development. Broadly, the objectives of the two programs are thus:

- *To provide the scientific basis upon which rehabilitation management decisions can be made, with the specific aim to increase the chances of successful ecological restoration of mined coastal dune forests.*
- *To provide RBM with scientifically sound information that will enable it to comply with the requirements of the ISO14001 environmental standards for companies.*
- *To further the University of Pretoria's primary aim of high-level training and education through innovative and applicable research.*
- *To improve scientific and general public perception of this restoration project's conservation value.*

To meet these objectives, the EcoIMP surveys herb, tree, millipede and bird assemblages either annually, semi-annually, or every third year (depending on the group – trees don't need to be surveyed as often as millipedes).

To evaluate whether the rate and direction of regeneration in these four groups on the post-mining CHRONOSEQUENCE is acceptable, we also survey a series of known-aged forest sites that were abandoned after historical disturbances such as slash-and-burn agriculture and township development. These spontaneously regenerating sites provide a roadmap for natural ecosystem recovery, a reference trajectory against which we can measure our human attempt at repairing an ecosystem (i.e. rehabilitation).

The target for rehabilitation is the restoration of a typical dune forest. We define this target in terms of the species composition (the identity and the abundance of each species that occurs on a particular site). But species composition is never exactly the same in all forest patches, or even in the same forest patch over time. This variation is natural and caused by a variety of ecological factors such as geographic limitations in the ranges of species (many tropical species reach the southern limit of their range here on the subtropical coast), competition, predation and local disturbances driven by chance and climate. Sometimes local populations go extinct for a while before being "rescued" by dispersal from other source populations.

All of these phenomena need to be captured by the restoration program. We therefore need to define the target as a "cloud" of possible outcomes in species compositions (or indeed of the value of any ecological variable), rather than as a static value. To define the target, we survey as many regional patches of dune forest as possible (the BENCHMARKS, or REFERENCE SITES). We then use indices of variability amongst the patches to demarcate the outer limits of the cloud of acceptable target values for the variables we measure.

BOX 5 continued

The natural chronosequence thus provides the target trajectory for the post-mining regenerating areas and the various undisturbed forests provide the target endpoint. We can now evaluate whether the observed patterns of change in variables point ***to the*** *recovery of a typical dune forest, or away from it and whether the rate of development is ecologically acceptable. To do this, we evaluate the variables recorded on the post-mining regenerating sites against the following (see figure at the end of Box 5):*

- *whether age-related trends on the post-mining chronosequence are stable over time (i.e., whether the pattern is the same every time we measure it),*
- *whether patterns on the post-mining regenerating sites mimic natural patterns,*
- *whether the overall developmental trend on the post-mining regenerating sites is towards the benchmark, and*
- *whether the value of any ecological variable on the oldest regenerating site is statistically similar to that of the benchmark.*

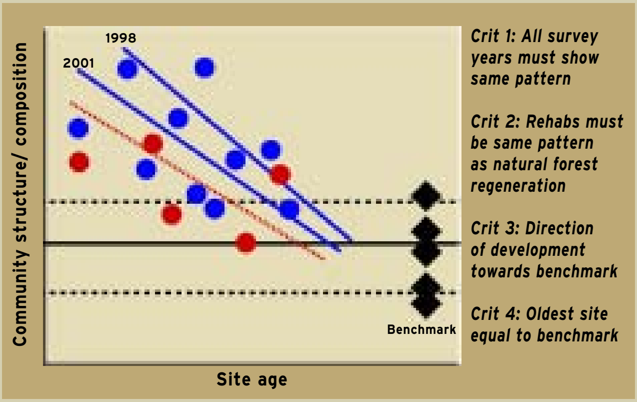
A map of the study area, showing the location of the different regenerating forest patches, and the benchmark forests. The "R" prefix denotes a rehabilitating site (there are currently seven of these, ranging from 1 to 27 years old), while the "S" prefix denotes naturally regenerating sites (nine sites, ranging from 5 to 53 years old). The undisturbed benchmark sites are indicated as Sokhulu, Mapelane, St L.1-8 (for "St Lucia") and Ecostrip (a strip of unmined forest between the beach and the rehabilitating areas). These benchmark sites represent the target for the restoration program.

BOX 5 continued

The EcoIMP is designed to be flexible, though. As we learn more about the value of particular ecological variables and groups as indicators of forest development, or about how these can be employed to yield more information, we adapt the way in which we measure and analyse the data. For instance, a current focus of the EcoIMP is to design a method to detect atypical changes that may otherwise go unnoticed.

The path of development may be affected by many factors. Clearly, the more we know about these factors, the better we will be able to manage and improve future development. In the ERRP we do exactly this – we investigate whether changes conform to ecological theory, and we investigate those factors that might influence colonization. These range from the effect of the landscape on dispersal between source areas and new habitats, to the effect of soil conditions and habitat structure on the chances for a forest species to establish a viable population.

The overall motivation for both the ERRP and the EcoIMP is a better understanding of the mechanics of dune forest re-assembly. Understanding forest re-assembly will directly enhance the practice and outcomes of restoration management and the principles that emerge from our studies will also continue to find a wider application in ecological restoration.



This figure explains the principle behind the evaluation of dune forest development. A community develops over time, so that we could expect an ecological variable to change as the site's age increases. Community development in the regenerating areas is represented by the blue (rehabilitating sites) and red (naturally regenerating sites) dots, and their correspondingly coloured trend lines. We also measure the particular variable in the benchmark forest (the black diamonds on the right-hand side of the graph). The target for community development is the average of that variable in the BENCHMARK forest, represented here by the solid horizontal line. The variability in the benchmark is represented by the dotted horizontal lines (the standard deviation or statistical variability). The regenerating sites are sampled every few years, so that many trend lines can be fitted across site age (in the graph the two blue lines represent, for illustration purposes, surveys conducted in 1998 and 2001). Our first criterion (1) asks if these blue lines have the same slope for every survey year (meaning that the developmental rate is stable). The second criterion (2) evaluates the average trend on the rehabilitating sites (blue line) against the trend on naturally regenerating areas (the red line). The two types of regenerating sites should develop at the same rate. The third criterion (3) asks if the trend is towards the benchmark value or away from it. Finally (4), if a regenerating site falls within the upper and lower dotted lines, it has a good chance of being statistically equal to the benchmark, at which point we can claim success.

The mechanics of dune forest restoration, the "how" and "why" of assisted ecosystem re-assembly, are studied in the Ecological Restoration Research Program (ERRP).

The objective of the ERRP is to support and inform management decisions flowing from the Ecological Monitoring Program. It also investigates associated theoretical problems. However, this hasn't always been the case. Since the start of the first research project on the dynamics of post-mining rodent and shrew assemblages in 1992, emphasis in the ERRP has changed from a description of changes in community STRUCTURE and COMPOSITION (of several different groups) to a more mechanistic investigation of the causes and consequences of colonization and extinction dynamics. Essentially most of our monitoring and supporting research is aimed at understanding how species colonize the new habitats, and what the resulting patterns in community composition mean for restoration management (see Box 5). We have, over the years, also investigated the development of soil chemical and physical properties (the functional part of ecosystem development), and larger-scale issues such as the conservation status of dune forests. The over-arching theme of our research is on how a dune forest is re-assembled after a disturbance, so that we can better assist forest recovery.

A synopsis of **ecological trends** in a regenerating dune forest

Studying a whole ecosystem

The research program includes organisms from eight biological groups. Plants (herb layer and woody plants separately), soil micro-arthropods, dung beetles, millipedes, beetles, spiders, rodents and shrews, and birds all have been studied since the inception of the programme in 1992. We have also studied the changes in soil nutrients (and how these are influenced by millipede activities), the conservation status of dune forest, and remote sensing as a tool in rehabilitation evaluation. Furthermore, a large part of our research is aimed at answering management questions about the quality of topsoil, for instance, or the rate of germination of different classes of seed. Here we provide a summary of the important ecological trends that have become apparent from the studies.

Soils

Many factors influence the chances of successfully restoring an ecosystem, but soil, because it is such an essential source of nutrients for plants, is arguably the single most important determinant of restoration success. Post-disturbance soil quality differs along many axes (the presence and concentration of particular minerals and toxic chemicals would for instance be just two of such axes), forming a gradient from suitable to unsuitable for a particular plant or animal species.

In practice, restoration efforts can be divided into those where starting soil quality is bad and those where it is good. Although some plants can grow in the most inhospitable conditions imaginable, it is essentially impossible to re-establish a whole forest ecosystem in poor quality soil. Bad soils are devoid of organic life, are polluted with toxic chemicals and high concentrations of minerals and have lost all semblance of structure. In such conditions, establishment of even the simplest ecosystems requires considerable and expensive intervention measures. Good quality soil, usually in cases where the topsoil from a pre-existing ecosystem has been preserved, retains some (or most) of its structure, almost all of its essential minerals and nutrients, and often a supply of seed that has been lying dormant for years. But perhaps most importantly, the micro- and macro-organisms that are vital for the breakdown of organic and inorganic compounds to the minerals and nutrients that plants need for growth, are also preserved with the topsoil. Topsoil therefore provides, in one single package, not only the resources (the minerals and nutrients), but also the machinery (the soil organisms) that can churn out plant food.

RBM's restoration effort starts off with the collection of topsoil in areas about to be mined. This dark-coloured topsoil, rich in organic compounds, essential minerals and soil organisms, is spread on the tailings behind the dredge pond. After seeding with a cover crop of annual plant species for soil stabilisation, and, if necessary, with the seed of the pioneer plant *Acacia kosiensis*, the forest ecosystem is allowed to develop without further assistance through succession (Box 4).

However, the topsoil's chemical and physical properties are not static. Three successive surveys[1, 2] on the changes in soil chemical and physical properties of regenerating and BENCHMARK (see glossary) sites showed that the initial stock of carbon and other organic compounds decreases by at least half soon after rehabilitation started, and by about half again within the first three to five years as the first pioneering plant community consumes it[1, 2]. After this, the soil carbon and organic content recovers at between 0.03% and 0.1% per year, as it is replaced by a maturing and sequentially more diverse plant assemblage. By 25 years after rehabilitation started, both these variables have regained between half and three quarters of their initial values, and organic content is statistically the same as that of benchmark soil[2]. These patterns are remarkably consistent, with the rate of accumulation differing by only 0.01% between successive survey years[2]. In general, all other minerals and physical properties we measured followed the same broad pattern of an initial decrease and a subsequent increase with stand age[1].

Arbuscular mycorrhiza, the fungi that live in an intimate symbiotic relationship with plants, are crucial to the functioning of almost every ecosystem on earth. These fungi infect the roots of most plant species, increasing their efficiency of uptake of many nutrients, but particularly phosphates, by several factors. They reproduce through microscopic spores released in the soils, and disperse on the feet of small animals and by wind. In our study area, mycorrhiza spores apparently survive the collection and re-spreading of topsoil, and successfully infect the roots of plants in the rehabilitation sites[3]. However, mycorrhizal diversity, as measured by the number of mycorrhiza morphotypes, apparently decreases over the first ten years of rehabilitation, before starting to increase again[3]. By 18 years after rehabilitation, the mycorrhizal community has recovered approximately half the diversity of the undisturbed forest reference site[3].

Development in the soil macro-arthropods, the tiny insects and Acari (mites and ticks) that live in the soils, is much slower than in any of the other groups that we have studied[4, 5]. Acari are more common than insects in all the soils that we sampled, but the community structure of both groups on the regenerating sites was significantly different from the undisturbed forest sites, with little indication that the communities developed as the sites aged[4, 5]. A multivariate analysis showed that contrary to expectation, community composition is only weakly related to soil chemical and physical properties[4, 5]. Overall, the structure and composition of soil macro-arthropod communities on regenerating sites may take long to recover, unless the limiting factors can be identified and managed.

We don't yet know to what extent the development of soil properties is dependent on community development in soil organisms. What evidence we have seems to suggest that this relationship is tenuous. We need more information here, as well as on the structure of soil micro-organism communities (bacteria and fungi) and their link to soil chemical properties. The lack of development in these communities may be because soil organisms find it disproportionately hard to disperse to new habitats because they have fewer dispersal options, or they may die during the re-spreading of topsoil. In view of the importance of soil to the functioning of a forest, we plan to focus on many of these aspects in our research.

Plants

Trees are the most visible part of any forest. But they are more than just the "poster boys" of the forest; functionally they are a keystone group because changes in their size and abundance determine what happens to almost all other forest organisms. They provide the crucial structural complexity that defines so many other species' habitat, and they provide food directly. The return of a typical group of mature dune forest tree species to the regenerating areas would be a significant sign of successful restoration indeed. Our monitoring data, and a predictive model, show that forest trees start colonizing soon after rehabilitation, that the rate of colonization is constant over time, and that by 60 years after rehabilitation we won't be able to distinguish the regenerating tree community statistically from a mature dune forest[6]. Moreover, regeneration on the post-mining areas is at least three times faster than on areas regenerating spontaneously after other types of disturbance, perhaps because the post-mining areas are protected from most of the vagaries of human use and are closer to source areas[2].

Our more recent studies seem to suggest that these recovery patterns are caused mostly by colonization of the small-seeded tree species, and that colonization of the large-seeded forest trees is lagging far behind – only 25% of forest trees with seed larger than 14mm have colonized, compared to 57% of species with seed smaller than 7mm[7]. It also appears that the closest populations of these large-seeded species, which are mostly dispersed by monkeys, tend to be in the large, old patches of forest about 10km north of the regenerating areas. These are interesting results, because a previous study has shown that vervet monkeys do indeed visit the regenerating areas, albeit not that often[8]. The distance to the source areas, and the presence of dispersing agents (the birds and monkeys that eat the fruit and so disperse the seeds in their droppings), will thus play an important role in forest regeneration. The results from this study may therefore suggest that we should assist dispersal of the large-seeded tree species, although it would also be necessary to establish whether they are not perhaps merely incapable of germinating in the woodland conditions.

The ecology of plant establishment, and germination in particular, will clearly always be an important factor that can change the course of forest development. The pioneer species *Acacia kosiensis*, for instance, produces prodigious numbers of seeds (up to 45 seeds per kg of total biomass or more) every season[9]. As is typical of pioneer tree species, these seeds can lie dormant in the topsoil for decades[9]. The result is that the topsoil is saturated with *A. kosiensis* seeds wherever this species has grown in the past, with seed densities reaching between 40 and 200 seeds m^2 [9, 10]. This species is the key to the rehabilitation process and studies on its germination conditions are ongoing. Preliminary findings show that fresh seeds germinate poorly. The thick protective outer layer of the seed needs to be scarified before a significant number will germinate[11]. But seeds that have been soaked in the top-

soil for years do not have the same problem[10, 12] – once there is a disturbance that removes other trees, these *Acacia* seeds quickly germinate to form dense thorny thickets. Their density rapidly decreases though, at a rate predicted by ecological theory. By 22 years after rehabilitation, although still the dominant canopy species, *A. kosiensis* density is only about 150 per hectare[9]. This is almost the end of the species' reign, because such a low density exposes more and more individuals to the vagaries of climate and pests, so that large gaps start appearing in the woodland canopy.

What happens after that is dictated by the number and diversity of broad-leaved forest tree saplings in amongst the tangled growth of plants on the woodland floor. This crop of broad-leaved trees is the future of the forest (although we have shown, through a Markov-chain model, that it is not possible to predict the end-state species composition from the current[13]). This is because the initial cohort of small-leaved, pioneering *A. kosiensis* trees apparently never replaces itself when individuals die[9], instead, the broad-leaved forest tree species take their place. In ecological terms there will thus be a fairly sudden change from the small-leaved *Acacia* canopy to a diverse broad-leaved forest canopy that allows little light through. This changeover is an important time for the regenerating area, and if the density of forest trees is too low at this stage, perhaps as a result of earlier disturbances, the regenerating area may be caught in an ALTERNATIVE STATE. Such disturbances may be caused by unnaturally high browsing levels. A study on the effects of cattle (ever-present illicit visitors to the regenerating areas) on the herb layer has shown that unless their stocking density is extremely high, these broad-leaved saplings will not be affected, but the cattle cause enough disturbance to increase the rate of invasion by exotic and other weedy species[14, 15]. Ultimately these may have a negative effect on the total rate of forest regeneration, as invasive species can probably out-compete native species.

On the whole, the community of herb layer plants in regenerating forests dance to a different tune to the trees. Our models predict that, on a broad level, the herb layer plants will probably take at least twice as long to resemble a forest herb layer community than the trees[2, 6, 16]. Indeed, the models predict that the forest herb community will never recover in aspects such as evenness or relative abundance[2, 6]. A model can of course be a good approximation of reality, but for the herbs, these empirical models are most likely wrong. The plant community of the herb layer is probably sensitive to the amount of light that reaches the woodland floor. Incident light affects plant growth in the most fundamental way imaginable. Very few plant species can grow in the low light conditions on the floor of a mature forest; those that do are specialised sciophytes (shade-loving) species. In contrast, the *Acacia* woodland canopy of the regenerating areas allows enough sun to penetrate for even many sun-loving stoloniferous grasses to grow there[14,15]. However, the amount of light in the regenerating forest does not change linearly, rather it will change in big steps over time as woodland (lots of light) is replaced by broad-leaved forest tree species that form a closed canopy (low light). We suspect that when the amount of light that reaches the forest floor decreases, the herb layer plant community will follow suit and will change to resemble that of a mature forest. This requires further investigation though, particularly because our most recent, regional survey of these plants showed that the species composition and structure of herb layer plants differ significantly, even between closely located mature forest patches (Unpublished data).

Our research on the plant communities here has intentionally avoided the classic plant ecological approach of defining and describing cohesive plant communities. This is because, in our experience of how communities are re-assembled, the classic approach is too static to take all the myriad combinations of species groups into account when deciding whether there is directional change in species composition. However, on another scale the mere description of a patch of vegetation as "mature forest", or "degraded woodland" can convey much about its current ecosystem properties, and its ecological history. For this reason, and with the management objective of determining topsoil quality in mind, we did a crude description of all vegetation patches in the unmined part of RBM's lease area, based only on appearance on aerial photographs and PHYSIOGNOMY[17]. Only about 15% of this unmined area is covered by undisturbed mature dune forest, with the rest covered by severely degraded forest or abandoned exotic plantations (~60%), current exotic plantations (~20%) and other vegetation units (~5%)[17]. This commissioned GIS study has allowed RBM to refine its topsoil management – it can now predict, at any stage of the mining operations, how much topsoil of what quality would be available.

Millipedes

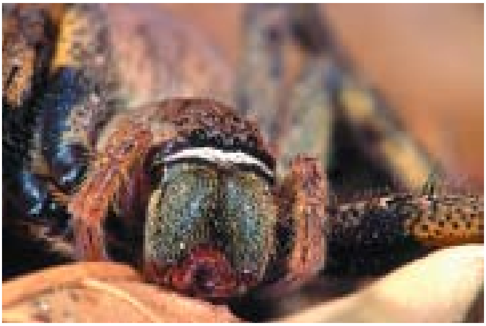
A mature forest obtains its nutrients and minerals largely from its own dead matter. All the nutrients and minerals in dead leaves, bark, and dead animals, are recycled to the soil, from where they are again available for plants to take up. In these coastal dune forests, millipedes do much of the first part of the recycling, because they consume the small detritus. These animals thus form one of the most important components in the functioning of a forest. It is therefore not surprising that such a large part of our research effort over the years has gone into a description of the structure of the forest millipede community and its development in regenerating forests, how the dominant species relate to each other, their autecology, and how millipedes recycle nutrients.

As with most of the other groups, the millipede community on regenerating stands changes over time to become more diverse, but also to more closely resemble the community of a mature dune forest in species composition[2, 6, 18, 19, 20]. These changes are apparently faster on the post-mining sites than on naturally regenerating sites, perhaps because of fewer disturbances there[2, 19, 20]. Although dune forests harbour many species with small

geographic ranges, the community seems to be dominated by three species that are variously dominant at different successional stages. Through breaking down litter, these three species all play a role in the accumulation of soil nutrients, helped along by soil bacteria[21]. However, the species differ in the extent to which they influence the rate of accumulation of the different nutrients in the soil. This is particularly true for carbon, which increases almost twice faster in soils under the millipede *Centrobolus fulgidus* than in soils under the closely related *C. richardi*[21].

Ecological theory dictates that two very similar species cannot coexist; yet of the three species in this last study, the two closely related *Centrobolus* species (*C. richardi and C. fulgidus*) are by far the most numerous and widely dispersed in the area, occurring together in almost all stands. They are also very similar in appearance, size, and autecology. It turns out that they manage to coexist in the same area through an elegant seasonal and height separation of their microhabitat[22]. *C. richardi*, which occasionally seemed to be less numerous in our data, apparently utilises the higher tree layer in the summer when *C. fulgidus* is dominant on the lower shrub layer[22]. When *C. fulgidus* becomes dormant in the winter, *C. richardi* moves down to occupy what may be a more productive habitat on the ground[22].

This seasonal separation of the habitat by the two species would suggest that they are either competing, or are differentially sensitive to microclimatic conditions (i.e. the temperature and humidity at different levels in the developing forest). To determine whether microclimate can explain their habitat preferences, we measured the ambient temperature and humidity levels at each millipede that we encountered[23]. The results from this study suggested a definite difference in the preferred microclimatic profile between the two species (*C. richardi* was encountered at a greater range of heights at intermediate temperatures and humidity levels, while *C. fulgidus* seemed to prefer a somewhat lower temperature-humidity combination)[23]. There was also no evidence of active competitive exclusion – quadrats with many *C. richardi* individuals often also held many *C. fulgidus* individuals[23]. Nevertheless, compared to the simple separation in height above the forest floor, this microclimatic effect was weak. We therefore concluded that the two species are probably competing, with *C. fulgidus* excluding *C. richardi* from the potentially better habitat of the lower stratum in summer[23]. The last word has not been said about the effect of microclimate, or about competition though. For instance, we don't know whether there is a particular temperature-humidity combination that will prevent a species from choosing a particular microhabitat. Moreover, the evidence is sometimes conflicting, with some results pointing to active competition and others not[22, 23]. We aim to investigate these aspects in a controlled experiment in the future.



Other invertebrates

Apart from millipedes, several invertebrate groups are important players in the functioning of a forest. We, and our associates, have described the development of community structure and composition in beetles (Coleoptera), spiders (Arachnida), dung beetles (Coleoptera: Scarabaeidae), and two major groups of soil organisms. One of these studies has shown that the regenerating areas are home to at least 125 beetle species, putting the diversity here on par with those of other developing communities[24]. Changes in beetle species diversity over time are the result of a turnover of species, suggesting that the colonisation patterns here are typical of succession[24].

Spider communities of the forest floor in regenerating areas also appear to be developing in the same way as vegetation communities do – they resemble a typical forest community more and more as the habitat age increases[25, 26]. However, multivariate statistical techniques showed that this apparent directional change is not a simple function of habitat age[26]. Spiders probably perceive the habitat sere (the set of sequentially-aged regenerating areas) as three distinct habitats, separated by distinct differences in vegetation cover below 1m and the amount and type of the leaf litter layer[26]. It is therefore unlikely that the recovery of vegetation structure will automatically be followed by a recovery of spider communities. Ultimately, successful restoration of spider communities will depend on whether the microhabitat in the woodland (the current stage of development in the regenerating areas), will develop to the point that it resembles that of a forest.

Most people associate dung beetles with savannas or grasslands. It is probably less well known that southern Africa is very rich in dung beetle species, with species ranging in size from a few millimetres to half the size of a human hand. Many of these species live underground, and many specialize on the dung of small mammals. The eastern coast of southern Africa is particularly well endowed with dung beetle species, some of which occur only in the Maputaland Centre of Endemism (Box 1), and many of which are highly specialised forest dwellers. Our study on dung beetles showed that early rehabilitation sites are dominated by species that tend to be widely distributed through the region[27]. The older the site becomes, the more it tends to be dominated by species with a local distribution. This trend was apparently determined by the relative differences in PHYSIOGNOMY (vegetation architecture) and microclimate between the regenerating areas and the undisturbed forests, implying that full restoration, as in spiders, will be dependent on the re-establishment of natural forest physiognomy and microclimate[27].

BIOFACT

ENDEMIC SPECIES: An endemic species is one that occurs only in a specific area. This area can be defined in many ways (it can be a political entity for instance), but its primary meaning is biogeographical. Because these species are unique in many ways, and often scarce, ecologists assign much importance to their conservation. There are many Centres of Endemism in the world (at least 18 major Centres are recognized in southern Africa), but Maputaland is unique in its high number of neo-endemics. These are species that have only relatively recently become distinct species, and indicates an active evolutionary process and a recent (about 1.75 million years) geological origin for the whole area.

The importance of microclimate for dung beetle community structure was confirmed by another study that compared the similarity of developing assemblages with those of undisturbed forests – changes in species composition closely followed changes in vegetation physiognomy and microclimate, so that older assemblages actually diverged from forest assemblages after an initial convergence[28].

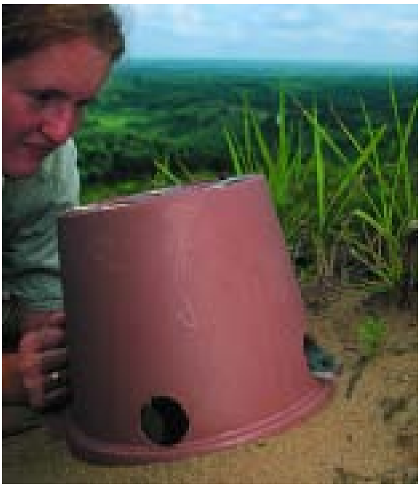
Small mammals

Although forests are not known for harbouring many mammal species or large groups of mammals, the small mammal (rodent and shrew) assemblage provides an interesting study of how a group at the top of the food chain is re-assembled after a disturbance[29, 30, 31, 32, 33, 34, 35, 36]. Atypical of forest organisms in general, the small mammal assemblage is dominated by only a few species[29, 30]. Three rodent species in particular, the multi-mammate mouse (*Mastomys natalensis*), the pouched mouse (*Saccostomus campestris*) and the red veld rat (*Aethomys chrysophilus*) apparently swop dominance at different stages of forest development[30]. Absolute density of small mammals is high initially while grasses and sedges dominate the vegetation, but it rapidly declines as the habitat grows older and more forest-like[29]. However, these patterns are not strong, and it is more likely that the apparent replacement of one species by another through competition is an artefact of a highly variable community[6, 29], driven by habitat structure and small-scale disturbances[29, 30, 33, 34]. Most rodent species seem to prefer disturbances, but the highest species richness occurs at intermediate stages of early forest development[34].

Because the multi-mammate mouse is such an important granivore in early stages of forest development, the use of insecticide dust on seed mixtures in rehabilitation may influence population numbers of the mice, and hence rodent community structure. However, a controlled experiment showed that insecticide treatment of seeds does not affect the survival or growth of mice[37, 38]. The characteristic rapid decline of multi-mammate mice numbers after rehabilitation is therefore likely a natural phenomenon caused by changes in their habitat and food resources[38].

That the rodent community is perhaps not competition driven was confirmed when, in a controlled experiment over two seasons, we supplied extra food (a grain mixture) to the rodents on early regenerating sites[35, 36]. The numbers of multi-mammate mice increased over the period of supplementation (compared to areas where no extra food was supplied), while the other four species remained at the same levels. Thus, even though one species increased when a limiting resource was increased, none of the others decreased, as one would have expected to happen if they were competing. This suggests that food is a limiting factor, more than interspecific interactions.

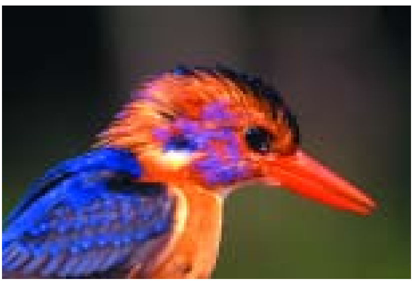
Nevertheless, overall the data from the small mammal community seems to suggest that they are not good indicators of forest regeneration. This is because they are so variable in structure (diversity and density) and composition, with no clear habitat age-related patterns in any of these[2, 6]. We therefore do not use small mammals as an indicator group in assessing restoration patterns and success. They continue to be studied though, because they provide excellent insight into how organisms are driven by changes in their habitat and resources.



Birds

Most ecologists agree that birds, being so dependent on intact habitats, are a good indicator group for changes in an ecosystem. This means that adverse or favourable changes in the larger ecosystem will be reflected in changes in the bird community. Forest birds in particular are a highly charismatic group, much studied in other parts of Africa, but also enjoying much attention from birdwatchers in general. A large part of our current and past research has consequently focused on this group, how the assemblage develops[2, 6, 16, 39, 40, 41], how they disperse to and establish in new habitats[42], and how they contribute to forest tree seed dispersal[43].

In general, the bird community appears to develop in an ordered fashion, changing from species characteristic of grassland, to a mixture of woodland and forest species, and eventually to mostly forest species[40]. Again, although there is some tenuous evidence that the hoverer guild is structured by competition[44], birds appear to be largely driven by changes in their habitat, with large old trees and a dense undergrowth being the most important determinants[40]. Bird communities on regional, unmined areas (such as exotic plantations and other disturbed areas) had the same structure as post-mining regenerating areas, but the species composition differed partially[41]. Moreover, community development was faster on the post-mining regenerating sites than on spontaneously regenerating sites[2, 6, 16]. Birds are proving to be excellent indicators of forest habitat development, being highly correlated with changes in the plant community[6].



Our current research on birds aims to determine which method is the best for surveys, and which bird species are not only using the post-mining regenerating areas as foraging habitat, but are also breeding there[42]. So far, our census methods for birds have been based on observations of individuals in structured line transect surveys. However, we know from past experience and from other studies that the line transect is not universally the best method, and that point counts may be better in some habitats. Provisional results indicate that the two methods' estimate of community variables is very similar, although the point transect method is probably more efficient because it detects more birds per minute of observation[42]. The results from this ongoing study will help us to determine which method to use in future surveys, and in how to interpret observation data (it tells us which proportion of observed birds also breed there).

But birds are also important dispersers of the seed of forest trees. Another current study is therefore investigating which birds consume which trees' seed, with the aim of eventually determining to what extent the spatial distribution, and hence the community structure of trees, is influenced by the distribution and abundance of birds[43].

Bigger issues

Most of our research over the last decade has been about the development of STRUCTURE in communities, and about what causes structure to develop. These studies have shown that successional patterns largely conform to theoretical predictions, in the sense that pioneer species colonize first, and are subsequently replaced by species characteristic of mature stages[45, 46]. However, we have also investigated several other issues about the regeneration of forests, not directly related to community structure. One such issue relates to the common observation, for almost all types of ecosystems, that high-density species also tend to be widely distributed. We were interested to determine whether this well-documented positive abundance-distribution relationship was also present in regenerating dune forests, and, if present, whether it remained the same across the developmental stages. Our study on the millipede and tree communities showed that the relationship exists for both communities, although our data could not elucidate a possible mechanism[47]. More interestingly though, the slope of the relationship becomes flatter as the habitat regeneration age increases, but only in trees, and only because the dominant pioneer species declined in abundance with time[47]. Furthermore, species tended to occupy different positions on the graph in different sites[47]. To determine whether this movement of species up and down the slope is a common phenomenon or unique to the post-mining regenerating sites, and whether dominance always determines the form of the slope, we intend repeating the study, using data from a wider geographic area and more species.

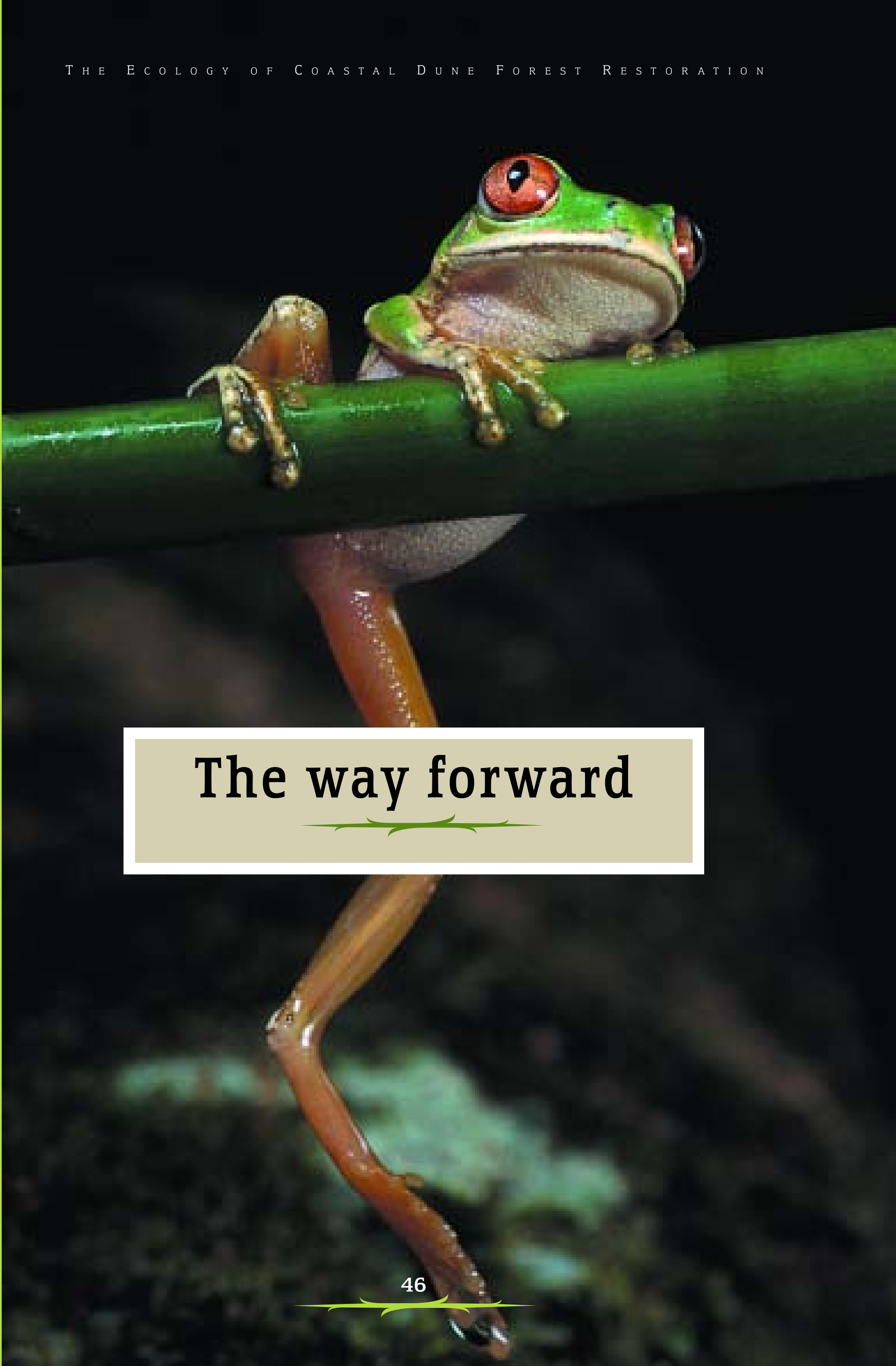
Abundance, and distribution, may of course also play a more mechanistic, direct role in the colonisation of new habitats by forest species. The more abundant a species is in its habitat, the more individuals of that species will be dispersing at any given time, and the more likely it is that it will be able to establish a population in a new habitat. In the same vein, one could expect species with large geographic ranges to somehow be better at colonizing new habitats. The result of this is that widely distributed, abundant species should be better at colonizing, and should have larger founder populations in new habitats, than rare species or species with small geographic ranges. We found that this is indeed the case for trees, millipedes and birds, but the effect appears to be modified to a large extent by other factors[26]. The result is that abundant and widespread species tend to colonize more often, and earlier, than rare species, but those rare species that do colonize do so at any stage of successional development[26].

An important issue in the management of any natural area is the construction of access roads – where should they be located and how many should there be? From the perspective of a regenerating forest community the answer is apparently: "nowhere near the middle and as few as possible". Two studies that we conducted, on the changes in microclimatic conditions from the edge of a road to the interior, and on the effects of these changes on rodent, bird and millipede assemblages, showed that the ecological footprint of a road is much wider than the road itself, at least for millipedes and birds[48, 49, 50]. The physical effect of management roads reaches up to 10m into the interior of a patch of forest, but the ecological effects are felt up to 100m from the road, depending on the site's post mining age (the effect is largest in the youngest stands and smallest in the unmined forest)[48, 49, 50]. Oddly, rodents appeared to be impervious to edge effects, but this could have been an artefact of low densities during the study period[49, 50].

A third issue is the ability of a naturally regenerating forest to capture carbon. High levels of carbon in our atmosphere, the result of the burning of unprecedented levels of carbon-based fuels by modern societies, can be modulated to an extent by sequestering it in plant and animal material. Because plants use carbon as a component in their physical structure, the restoration of forests may contribute significantly to this carbon sequestration, and the maintenance and protection of such a forest may create a valuable carbon sink. However, the question is now whether a naturally regenerating forest can compete with a commercial plantation, both in the absolute mass of carbon stored in its vegetation and soils, and in its economic potential. One of our ongoing studies is to compare the rate and efficiency of biomass (and hence carbon) accrual in both regenerating dune forests and plantations of *Casuarina equisetifolia* (beefwood). Preliminary results suggest that there is more carbon in the soil and herb layers of regenerating dune forests than in the same layers in beefwood plantations. However, in the wood and litter layers, this pattern is reversed[51].

The analysis of spectral data from particularly the Landsat satellites (remote sensing) has seen increased use in natural resource management over the last decade. This technique allows a rapid assessment of vegetation types over large areas at relatively small cost, but requires careful calibration. We tested whether this technique could be used as an alternative method to assess restoration success[52]. The results from this study showed that the analysis of remotely sensed data could distinguish between young regenerating sites and the rest, as well as between degraded forest or plantations and undisturbed forests[52]. But it couldn't adequately resolve the finer differences between intermediately aged and old regenerating sites, or between older regenerating sites and undisturbed forest[52]. This tool therefore has limited use in the fine-scale analysis of dune forest development, but is ideal for large-scale analyses[52].

We applied this large-scale potential of remote sensing analysis to good effect in another study, which determined the conservation context of dune forest, especially in light of its status as an ecotype in the Maputaland Centre of Endemism. This study showed that a surprisingly large proportion (60%) of extant dune forests is under some form of protection[53]. However, most of the remaining dune forest outside protected areas is either under threat of mining or other forms of development, or of being so severely fragmented that the remaining patches probably won't be able to support sustainable ecosystems[53]. Moreover, the 60% that is currently being protected should be viewed in the perspective of the human-associated loss, over the last century, of approximately 80% of dune forests all along their range. This study concluded that there is thus no place for complacency, and that the rehabilitation program of Richards Bay Minerals will contribute immensely to the de-fragmentation of dune forests, and the restoration of sustainable ecosystem processes in dune forests.



The way forward

The 13-year Ecological Monitoring Program (EcolMP), and the supporting Ecological Restoration Research Program (ERRP), is an insurance policy for RBM's rehabilitation program (see Box 5). Rehabilitation without continuous evaluation against set ecological criteria, and without directed scientific research, is like a marksman shooting blindly at a target. There is of course always a chance that the target might be hit, but that chance is very small. In the serious business of repairing human damage to nature, where failure can be irreversible, this is not good enough; we would much prefer to be assured of success. What is needed is some tool that will not only open the eyes of the marksman and allow him to take better aim, but will also steer the bullet to the target. Essentially, the research and monitoring programs do this by providing the information on which management decisions can be based. Informed management can mitigate against dispersal constraints, for instance, or against the negative effects of exotic invasive species. In this way, the chances of successfully restoring a typical dune forest are increased.

The monitoring and supporting research programs have produced a wealth of information on how a wide array of coastal dune forest taxa, from tiny soil organisms to large trees, are re-assembled after a disturbance. Most of the patterns that we found suggest that the rehabilitation program may successfully restore a coastal dune forest, and do so within an ecologically reasonable time. As a first approximation, it might thus be valid to conclude that change in community structure and function is not a capricious interaction between the environment and contingent history. Such a result is of course extremely attractive to a restoration ecologist, because it implies that an ecosystem, in all its complexity, may be re-assembled under human supervision.

So, to the question of whether dune forests can be restored, we have to unequivocally answer "yes". From that perspective, and with the proper scientific basis, dune forest restoration can clearly contribute to the conservation of forest biodiversity – it can decrease fragmentation, restore populations of forest species, and allow the return of ecological processes that are typical of forests in Maputaland. More importantly, it also allows an alternative to Cassandra; ecological restoration and restoration ecology provides an opportunity for conservation to change from a crisis discipline to being a pro-active and custodial activity of society.

But there is a catch. Ecological theory and practical experience would caution against too much hubris when trying to stitch such a complex beast back together again. Although the current trends are encouraging, they are all empirical (meaning that there is no real reason to expect that they will and must continue). Indeed, some of our latest findings on tree colonization would seem to suggest that the patterns we found tell only part of the story – many forest tree specialists, with large, monkey-dispersed fruit and seed find it very hard to colonize new habitats. Although we still know far too little about dispersal in forest species, these findings do point out nicely that many factors can influence the rate of recovery for a particular group, or even completely prevent recovery. Ignoring these signs could be fatal; we might end up not with a restored forest in our backyards, but with egg on our faces.

The importance of sound scientific research to inform management decisions is obvious. But research that is conducted in a vacuum can be as much a waste of time as shooting blindly at a target. We therefore base the questions that we ask in the EcolMP, and the supporting ERRP, on proven ecological theories and principles. In practice this means that we focus on the two fundamental processes that lead to community recovery: colonization and extinction (see Box 5). We have begun with a number of studies on dispersal and establishment processes in forest animals and plants, but many more questions flow almost automatically from such a mechanistic framework. For instance, how many and which species must still colonize in order to maintain or improve current recovery trends? When is recovery too slow? How do the population dynamics of rare species influence their chances to find and occupy new habitats? Our research focus has changed over the years, and will change again as we adapt the program to provide the most cost-efficient answers. We will continue to ask questions such as the above, but also focus more and more on increasing our ability to predict what community composition will be in the future.

The company's financial and philosophical commitment to restoration and research has so far ensured that rehabilitation has been largely successful. But it is their continued commitment, not only to the principle of best practice in rehabilitation, but also to catering for the unforeseen through support for innovative research, that will ensure success in the future.

Glossary

ALTERNATIVE STATE: In the ecologist's idiom, a "state" is a particular combination of species that occurs together in a community. However, because the factors that influence community development are complex, this specific composition is not the only one possible. Like a marble that may end up in one of many possible troughs on a dimpled plane, post-disturbance development can end up in any one of several apparently stable alternative species compositions.

BENCHMARK: The characteristic species composition, structure and function of an undisturbed, mature forest is the *benchmark*, or target, against which restoration success is actually measured. In its strict sense, *benchmark* therefore refers to the value of the ecosystem indicator, but it is also often used in shorthand fashion to refer to the mature forest site itself.

BIOLOGICAL DIVERSITY: An encompassing term describing the diversity of all living things. This is usually shortened to 'biodiversity' and includes the genetic diversity of a species, the actual numbers of species in an ecosystem and their abundances, and the diversity of ecosystems or habitats.

CHRONOSEQUENCE: A set of regenerating sites of sequential and known post-disturbance age that are surveyed at about the same time. The resulting pattern of differences across this age gradient is then used to infer what the pattern would have looked like, had any one of the sites been sampled over time for a period equal to the age of the oldest site. Functionally, this is the same as a successional "sere".

COMMUNITY ASSEMBLY: This is the process of re-constituting a community after a disturbance by the addition of species that typically occur in it. Species additions occur naturally, but can be assisted as part of a restoration effort.

COMPOSITION: This is the identity (and sometimes also the abundance) of the species that occur in a particular assemblage. This is obviously more than just the number of species, and is perhaps the most important variable to evaluate in a restoration effort.

ECOLOGICAL RESTORATION: The process of assisting the recovery of a disturbed ecosystem. It implies a full recovery, including STRUCTURE, COMPOSITION and FUNCTION, but does not imply a static endpoint. Instead, it specifically allows a natural amount of variability in all the important ecological indicators (such as local or alpha diversity, species composition, and turnover rates to name a few).

FUNCTION: Function variously refers to the way an ecosystem cycles nutrients and energy (converting it to biomass in the process), or to the way in which different species, or different functional groups of species, interact with each other. There are many types of interactions, but most centre on competition between similar species, or feeding by one group of species on another.

PERSISTENT STATE: If the identity of the species in an ecosystem does not change much over time, that particular species composition is a persistent state. In a sense, it refers to the same phenomenon as the term climax (see Biofact on succession), but without the implied determinism (because many persistent states are possible, the boundaries between different states can be fuzzy, and none has logical supremacy over any of the others).

PHYSIOGNOMY: The outward appearance of the vegetation, made up of the architecture (characteristic layering of the vegetation, from the herb-layer through the sub-canopy layer to the canopy layer) and life-form (the growth form, such as tree, shrub or creeper) of the plants in a community.

REFERENCE SITES: If the objective of a restoration program is to restore a forest, as is the case here, then all undisturbed, mature forests would be reference sites, and the values of the indicators of ecosystem integrity on these sites would be the BENCHMARK for ecosystem development.

REHABILITATION: This is the practical part of ECOLOGICAL RESTORATION, the application of a set of techniques and methods in order to reach the objective of restoring a particular ecosystem.

RESTORATION ECOLOGY: The study of the ecological phenomena and principles associated with ECOLOGICAL RESTORATION. Because ecological restoration is an assisted recovery of ecosystem structure and function, restoration ecology most often focuses on processes such as succession, dispersal, colonization, and COMMUNITY ASSEMBLY.

REVEGETATION: Revegetation implies restoration without the objective of reinstating a particular, native ecosystem. In revegetation, any plant species would do (for instance, sowing a mixture of commercially available grasses on mine tailings for soil stabilisation), although a commercial crop or timber-producing trees are often used.

STRUCTURE: Structure describes all aspects of the diversity of a community. Diversity is a complex variable, and can be measured in many ways. In its simplest form this is the number of species that occur in an area, but more complex metrics include the number of individuals of all species.

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Richards Bay Minerals, The National Research Foundation (NRF) and the Department of Trade and Industry (DTI) has supported this research.

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