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The Miombo Network: Framework for a Terrestrial Transect Study of Land-Use and Land-Cover Change in the Miombo Ecosystems of Central Africa

The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP) of the International Council of Scientific Unions (ICSU)
Stockholm, Sweden

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The Miombo Network: Framework for a Terrestrial Transect Study of Land-Use and Land-Cover Change in the Miombo Ecosystems of Central Africa

Conclusions of the Miombo Network Workshop
Zomba, Malawi, December 1995

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Cover Photographs:

"Woodland"	Late dry season view of dry miombo woodland, Marondera, Zimbabwe. This woodland has been undisturbed for 45 years (photo. P.G.H. Frost)
"Fire"	Dry season fires are a prominent feature in the dynamics of miombo woodlands, suppressing woody regrowth and opening up the canopy. They are also a substantial source of emissions of greenhouse gases, Kaoma, Zambia (photo. P.G.H. Frost)
"Charcoal"	Charcoal produced from miombo trees is widely used as a source of fuel, Maputo, Mozambique (photo. P.V. Desanker)
"Traditional Small Grain"	Women harvesting finger millet, *Eleusine coracina*, a tradition small grain, Zimuto, Zimbabwe (photo. P.G.H. Frost).

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Executive Summary

This report describes the strategy for the Miombo Network Initiative, developed at an IGBP intercore-project workshop in Malawi in December 1995 and further refined during the Land Use and Cover Change (LUCC) Open Science Meeting in January, 1996 and through consultation and review by the LUCC Scientific Steering Committee (SSC). The Miombo Network comprises of an international network of researchers working in concert on a 'community' research agenda developed to address the critical global change research questions for the miombo woodland ecosystems. The network also addresses capacity building and training needs in the Central, Eastern and Southern Africa (SAF) region, of the Global Change System for Analysis Research and Training (START). The research strategy described here provides the basis for a proposed IGBP Terrestrial Transect study of land cover and land use changes in the miombo ecosystems of Central Africa. It therefore resides administratively within the LUCC programme with linkages to other Programme Elements of the IGBP such as Global Change and Terrestrial Ecosystems (GCTE).

The report provides the framework for research activities aimed at understanding how land use is affecting land cover and associated ecosystem processes; assessing what contribution these changes are making to global change; and predicting what effects global change in turn could have on land use dynamics and ecosystem structure and function. The key issues identified are:

- Patterns, causes and rates of change in land cover in relation to land use
- Consequences of land-use and land-cover changes on regional climate, natural resources, hydrology, carbon storage and trace gas emissions
- Determinants of the distribution of species and ecosystems in miombo
- Fundamental questions of miombo ecosystem structure and function.

Seven core experiments were proposed during the meeting, each addressing a critical objective relating to miombo ecosystems. These were (in no particular order):

- Land use dynamics
- Land cover dynamics

- Ecosystem dynamics and disturbance
- Nutrient limitation in miombo
- Biogeography and distribution of miombo
- Regional primary production and carbon balance of miombo
- Sustainable natural resource management.

In addition a number of integrating activities are proposed, including modelling, developing shared databases, and building regional research capacity. Each core experiment will be undertaken by a consortium of participating institutions and individuals at a network of sites across the miombo region. A Task Team (TT) for the Miombo Network will guide the scientific content and implementation of the projects. The TT will consist of regional and international representatives of participating IGBP and the International Human Dimensions Programme on Global Environmental Change (IHDP) programme elements. It is proposed that a Network Coordinator (NC), appointed by and responsible to the TT, will facilitate the activities of the network. An interim TT has been set up to oversee the launch of the programme and to consolidate the establishment of the Miombo Network

The initial phase of the programme will run for five years (1996-2000), building strongly on existing activities. Individual scientists or groups of scientists will develop specific proposals and seek funding for the core experiments in liaison with the TT and the NC. One of the first activities of the network will be to produce, in collaboration with Data and Information Systems (IGBP-DIS), a regional database on CD-ROM to facilitate interdisciplinary research.

Capacity building and research proposals from the initial phases of implementation are being submitted to funding agencies by START, LUCC and GCTE.

The Zomba workshop was jointly funded by the US National Science Foundation (International Programmes) and by the IGBP Secretariat.

Introduction

Background

The Miombo Network is an activity of the IGBP/IHDP Research Programme LUCC organized within the framework of the IGBP Terrestrial Transects studies (Koch *et al.* 1995) within START's SAF region. The aims of the Network are to understand how land use is affecting land cover and associated ecosystem processes in the miombo ecosystems of Central Africa; to assess what contribution these changes are making to global change; and to predict what effects global change in turn could have on land use dynamics and ecosystem structure and function. Given the focus on land-use and land-cover change, the administrative responsibility for the Miombo Network will reside with LUCC. As such this activity has been developed in close collaboration with LUCC and utilized the LUCC Science Plan as a framework. Since changes in land use and cover affect ecosystems and other biophysical systems, the Miombo Network activity recognizes the need to incorporate ecosystem dynamics and develop links to GCTE and other Programme Elements in a truly trans-programme-element fashion.

This report describes the strategy for the Miombo Network Initiative, developed at an IGBP intercore-project workshop in Malawi in December 1995 and further refined during the Land Use and Cover Change (LUCC) Open Science Meeting in January, 1996 and through consultation and review by the LUCC SSC. The initiative was also discussed at a number of meetings preceding the Zomba workshop, as shown in Box 1. The Zomba workshop was jointly funded by the US National Science Foundation (International Programmes) and by the IGBP Secretariat.

The rationale for the proposed research programme stems from concern for a better understanding of the long-term environmental and socio-economic effects of changes in the kinds and intensities of land use in the dry forests and woodlands of the tropics. To date, most attention has been focused on land-use and land-cover changes in tropical wet and moist forests, primarily because of the implications for global carbon cycling of the net release to the atmosphere of carbon stored in the vegetation and soils, and for the loss of biodiversity (Myers 1980, Houghton 1990, Houghton and Skole 1990). Much less attention has been paid to the widespread

changes occurring in tropical dry forests and woodlands, ecosystems on which a majority of rural people in tropical countries depend for their livelihoods, and which are arguably among the most threatened of tropical ecosystems (Janzen 1988). These ecosystems cover approximately 7.7 million km^2 (42 % of tropical forested land) and contain 22-29 % of the carbon stored in tropical forests and underlying soils (Brown and Lugo 1982, Solomon *et al.* 1993). They are important sources of reactive and radiatively active trace gases through biomass burning, termite activity, large mammalian herbivores, and plant and soil processes driven by marked seasonal fluctuations in moisture availability. The largest area of tropical dry forests and woodlands is situated in Africa (5.5 million km^2), about half of which occurs in the miombo region of Central Africa.

Box 1

Meetings leading to the Miombo Network Initiative.

1. IGBP/START/IGAC/GCTE Workshop on African Savannas and the Global Atmosphere, Victoria Falls, Zimbabwe, June 1993 (Justice *et al.* 1994 [IGBP Report 31, 1994]).
2. START Regional Workshop on Global Changes in Southern, Central and Eastern Africa, Gaborone, Botswana, July 1994 (Virji and Fleming 1996).
3. IGBP Regional Workshop on Global Changes in Southern Africa, Pretoria, South Africa, April 1995.
4. Miombo Network Meeting, Zomba, Malawi, December 1995, and LUCC Open Science Meeting, Amsterdam, Netherlands, January 1996.
5. Review and discussion held at the LUCC SSC meeting, 12-14 October 1996.

What Is Miombo and Why Is It Important?

Miombo is a vernacular word that has been adopted by ecologists to describe those woodland ecosystems dominated by trees in the genera *Brachystegia*, *Julbernardia* and *Isoberlinia* of the family Fabaceae, subfamily Caesalpinioideae (CSA/CCTA 1960, Wild and Fernandes 1967). Such woodlands extend across about 2.8 million km^2 of the southern subhumid tropical zone from Tanzania and Zaire in the north, through Zambia, Malawi and eastern Angola, to Zimbabwe and Mozambique in the south. Their distribution largely coincides with the flat to gently undulating African (early Tertiary) and post-African I (Miocene) planation surfaces that form the Central African plateau. The soils are predominantly infertile and are derived from underlying acid, crystalline rocks of the Basement Complex. These woodlands constitute the largest more-or-less contiguous block of deciduous tropical woodlands and dry forests in the world.

Interspersed within the woodlands are broad, grassy depressions (called *dambos* or *mbuga* in the vernacular, see Figure 1[a]). These seasonally waterlogged bottomlands can cover up to 40 % of the landscape in some areas. Dambos are not old river systems, as is often supposed, but are set into the landscape through differential weathering and subsurface removal of material by the lateral flow of groundwater (McFarlane and Whitlow 1990). They are important sites for cultivation and livestock grazing .

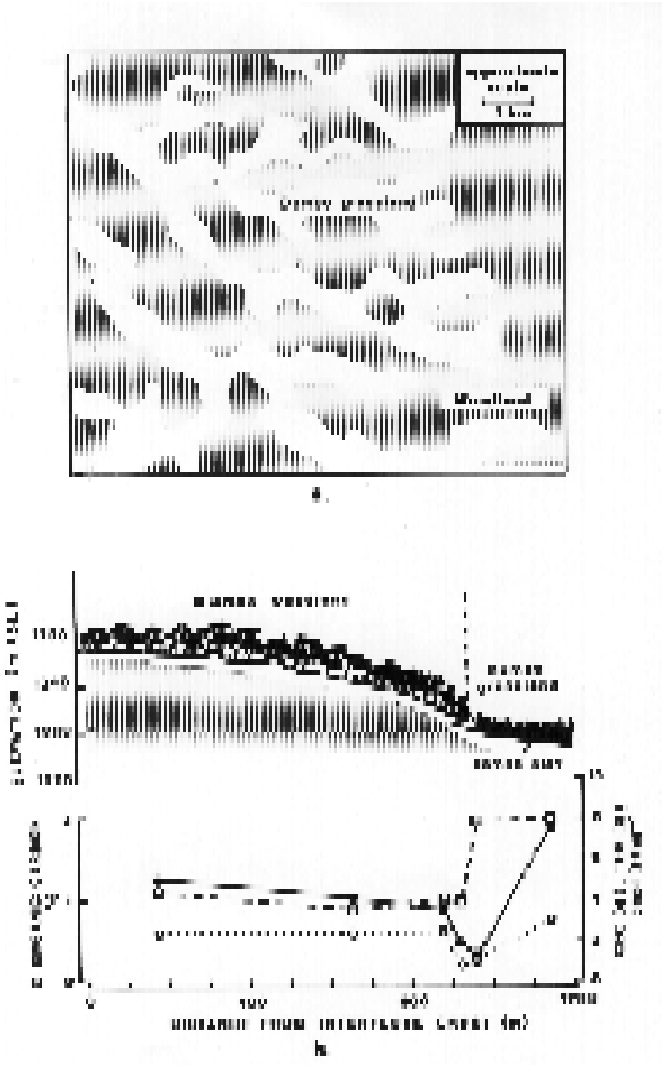
The soils of the miombo landscape form a catenary sequence, with well-drained, deeply weathered soils on the higher areas (often with lithosols on the ridge crests in drier areas) giving way to a narrow zone of sandy soils along the footslopes and then to imperfectly- to poorly-drained vertisols in the dambo (Watson 1964, Webster 1965). The dambo clay is largely smectitic and formed *in-situ* by the concentration of aluminium, silica and bases leached from the interfluves (McFarlane and Whitlow 1990). The basic landscape unit in miombo therefore comprises miombo woodland on the well-drained soils of the interfluve giving way abruptly at the footslope to hydromorphic grasslands on vertisols in the dambo (Figure 1[b]). The sharp transition between woodland and grassland reflects the point where the wet-season water table reaches the surface.

The components of these landscapes are strongly linked by the movement of water, soil and nutrients downslope; by the return of nutrients upslope through animal activity and atmospheric transport; by animal movements and fire; and by patterns of land use. An integrated study of these components is therefore essential. For this reason, the narrow botanical use of the term 'miombo' is inappropriate for this programme. In this report the term is used more broadly to encompass not only the woodlands themselves but also the associated land types within the same ecosystem. For the purposes of this programme, therefore, miombo is defined as follows:

Miombo encompasses those southern, Central and East African ecosystems occurring under a hot, seasonally wet climate on soils derived from acid crystalline bedrock, in regions where the woody component of the vegetation is normally dominated by species in the subfamily Caesalpinioideae (family Fabaceae), particularly in the genera *Brachystegia, Julbernardia* and *Isoberlinia*.

Figure 1

The miombo landscape: (a) a plan section showing the interdigitation of woodland (stippled) and dambo grasslands (clear); (b) a cross-section profile down a catena showing variations in soil properties and vegetation structure (topographic details and data on organic carbon, cation exchange capacity (CEC) and total exchangeable bases (TEB) from Webster (1965). The rolling relief is typical of the undulating erosion of the Central African Shield.



The area which satisfies this definition is shown in Figure 2 (see page 65). Ecologically similar *Isoberlinia* woodlands, lacking *Brachystegia* and *Julbernardia*, form the Guinea savannas of West Africa (White 1983). Woodlands dominated by related genera, principally *Baikiaea*, *Pterocarpus, Erythrophleum*, *Burkea* and *Cryptosepalum*, but differing ecologically in important ways, occur on sandy soils on the fringes of the core miombo region, most notably on Kalahari sands. At a global scale, the ecology of miombo ecosystems is closely related to that of the *cerrado* and related ecosystems of South America, the dipterocarp woodlands of south-east Asia and the monsoonal tallgrass eucalypt woodlands of northern Australia. Together these ecosystems occupy about 6% of the global land surface.

Miombo ecosystems directly support the livelihoods of about 39 million people in seven Central African countries, including some with among the lowest *per capita* income and highest *per capita* population growth rates in the world. A further 15 million people living in towns and cities throughout the region also depend on food, fibre, fuelwood and charcoal produced in miombo. Estimated woody biomass fuel consumption alone amounts to about 48 Tg yr^{-1}, releasing almost 22 Tg C. Other natural and anthropogenic processes, such as wildland burning, clearance of land for cultivation, slash-and-burn agriculture and the cultivation of wetlands, also contribute unquantified amounts of trace gases to the atmosphere, as well as altering the nature of the land cover and hydrological processes. On a more positive note, about 9 % of the region is protected as national parks, safari areas, and wildlife and forest reserves. Moreover, important advances have been made towards developing community-based natural resource management programmes, initially based on the sustainable use of wildlife but increasingly being extended to woodland resources in general (Child 1995, Bradley and McNamara 1993, Dewees 1994).

Given the predominance of woodland cover and the areal extent of miombo, the region has the potential to be either a source or a sink for carbon in the global carbon cycle, depending on the land-management practices adopted. The research activities proposed here are designed to provide a better understanding of the processes involved in land-use and land-cover changes, their socio-economic and biophysical contexts, and their global and regional consequences, as an input to the development of policies and programmes aimed at encouraging sustainable patterns of resource use.

An Overview of Miombo Ecology

Miombo has been portrayed as the archetype of moist-dystrophic savanna ecosystems (Huntley 1982, Frost *et al*. 1986). The vegetation, landscapes, and ecology of miombo ecosystems have been described by Malaisse (1978a), White (1983), Cole (1986) and Chidumayo (1993), among others. The following overview of miombo ecology is paraphrased from a review by Frost (1996).

The unifying features of miombo ecosystems, as defined in the previous section and elaborated on below, are:

- The upland soils are predominantly alfisols, oxisols and ultisols - infertile, with low cation exchange capacities (2-18 cmol[+] kg^{-1}), low total exchangeable bases (1-15 cmol[+] kg^{-1}), high acidity (pH 4-6 in $CaCl_2$), low available phosphorus (9-18 ppm), and a dominance of low-activity clays and sesquioxides, while the bottomland soils are predominantly gleysols and vertisols

- The dominant climatic feature is the marked seasonality of rainfall, with more than 95% of the 700-1 400 mm MAP falling during a 5-7 month, hot summer wet season (mean annual temperatures 18-23 ^{o}C, mean maximum temperatures 24-30 ^{o}C), which results in marked seasonality of plant production, growth, reproduction, and decay

- Most of the trees are deciduous but produce new leaves before the rains, drawing on substantial internal reserves

- The woodlands are dominated by broad-leafed, thornless trees of the subfamily Caesalpinioideae (family Fabaceae), while the grasses mainly comprise species in the family Andropogoneae

- Woody plants make up more than 95% of total plant biomass in mature woodlands but grasses predominate in dambos

- The dominant tree genera are all ectomycorrhizal

- The biomass of, and consumption by, indigenous large herbivorous mammals is generally low

- Consumption by herbivorous invertebrates is generally low though episodic outbreaks occur every few years

- Fire is frequent and important, both as an ecological factor and as a management tool

- Miombo ecosystems have been occupied and used by people for millennia, with slash-and-burn agriculture in the woodlands and cultivation of dambos major traditional forms of land use, though there are currently profound changes occurring in both the kinds and intensity of use.

One of the characteristic features of miombo woodland is its apparent uniformity over large regions. The woodland typically comprises an upper canopy of pagoda- or umbrella-shaped trees, occasionally with a scattered layer of subcanopy trees, and a discontinuous understorey of shrubs and saplings with a patchy herbaceous layer of grasses, forbs and suffrutices. This uniformity is due partly to the remarkably similar physiognomy of the dominant canopy trees, a reflection of their origins in the Caesalpinioideae, and partly to broadly similar environmental conditions across the region.

Differences in structure and species composition occur along rainfall gradients, from the drier fringes of the miombo region to the wetter core. White (1983) divided miombo into wet and dry types. Wet miombo is centred on eastern Angola, northern Zambia, south western Tanzania and central Malawi in areas receiving more than 1000 mm rainfall per year. Canopy height is usually greater than 15 m, reflecting the generally deeper and moister soils which create favourable conditions for growth. The vegetation is floristically rich and includes nearly all of the characteristic miombo species. Dry miombo occurs in Zimbabwe, central Tanzania, and the southern areas of Mozambique, Malawi and Zambia, in areas receiving less than 1000 mm rainfall annually. Canopy height is shorter than 15 m and the vegetation is floristically impoverished. Many of the dominant canopy tree species of the wet miombo are either absent or local in occurrence.

The present-day distribution of miombo reflects its history, principally past climatic changes and past and present human activities, though the scarcity of well preserved and accurately dated pollen profiles from Central Africa currently hampers the detailed reconstruction of the palaeoenvironments and past vegetation of the region (Scott 1984). Sediment cores containing *Brachystegia* pollen and covering various periods over the past 38 kyr have been recovered from a number of sites across northern Zambia (Lawton 1963, Clark and Van Zinderen Bakker 1964, Livingstone 1971), and from the southern basin of Lake Tanganyika, Tanzania (Vincens 1991), all near the centre of distribution of miombo. *Brachystegia* pollen has also been recovered from cores taken in the Inyanga highlands, Zimbabwe, at the present upper altitudinal limit of *Brachystegia* (Tomlinson 1974), and at Dundo, Angola (Van Zinderen Bakker and Clark 1962), close to the current lower altitudinal limit, adjacent to the lowland moist tropical forests of Zaire. In addition, traces of *Brachystegia* pollen have been found in 1-4 kyr BP sediments from near Naboomspruit and Pretoria, South Africa (Scott 1982, 1983), well beyond the present southern limit of the genus.

Brachystegia appears to have been widespread across Central Africa prior to the Last Glacial Maximum, but at the height of the glaciation, around 19 kyr BP, the vegetation became more open with Compositae, *Cliffortia* and *Cyathea* dominant, all elements of the present-day montane flora of Central Africa. This open vegetation was later replaced by *Podocarpus*, *Olea*, *Myrica* and Ericaceae (Scott 1984, Vincens 1991). Interpretations of these data, together with general circulation model (GCM) simulations of palaeoclimates, suggest that at the Last Glacial Maximum around 18 kyr BP the climate was about 3-5 ^{o}C cooler, and mean annual precipitation about 250 mm lower, than now (Vincens *et al.* 1993, Jolly *et al.* in press). This would have produced widespread change in the distribution of miombo, with the woodland vegetation of the central plateau probably being displaced to lower altitudes as the climate became cooler and drier.

With the amelioration of climate during the Holocene, *Brachystegia* again became a prominent component of the plateau vegetation. Subsequent expansions and contractions are suggested by changes in pollen abundance in late-Holocene sediments from the Inyanga highlands, where the genus had become well established by 4.7 kyr BP (Tomlinson 1974), and by traces of *Brachystegia* pollen in 2-4 kyr BP and < 1 kyr BP sediments from near Naboomspruit, South Africa (Scott 1982) and in < 1 kyr BP sediments from Pretoria (Scott 1983). The marked northwards contraction in the geographic range of *Brachystegia* in the past 1 000 yrs from sites more than 400 km south of its present distribution in Zimbabwe implies either a sudden change in climate during that period, something for which there is no evidence (Scott 1984), or that relatively minor shifts in temperature and moisture regimes during that period adversely affected the population dynamics of *Brachystegia* at its geographical limits.

Within the broad divisions between wet and dry miombo, there is much local variation in composition and structure in relation to soil depth, texture and drainage; fire regime; wildlife impact; and past and present land use. Aboveground woody biomass of old-growth stands in wet miombo averages about 90 Mg DM ha^{-1} (range 47-144 Mg ha^{-1}), while that of old-growth stands in dry miombo is generally lower, averaging 55 Mg DM ha^{-1} (range 21-84 Mg DM ha^{-1}) (Malaisse 1978a, Guy 1981, Stromgaard 1985, Chidumayo 1987b 1988 1990 1991, Frost 1996). The biomass of disturbed woodlands is lower still. Mean aboveground biomass increases with increasing mean annual rainfall of a site. Recorded mean annual increments of biomass in coppice woodland are 1.2-2.0 Mg ha^{-1} yr^{-1} in dry miombo and 2.2-3.4 Mg ha^{-1} yr^{-1} in wet miombo, about 4-7 % of aboveground biomass (Chidumayo 1990 1991 1993).

Much less is known about the amount of biomass belowground. Miombo species have horizontally and vertically extensive root systems. Maximum recorded lateral distances are 27 m (*J. globiflora*: Strang 1965) and 15 m (*B. longifolia*, *B. spiciformis* and *J. paniculata*: Savory 1963). The tap roots of these species can exceed 5 m in deep soils. Available estimates of belowground biomass are 7-39 Mg ha^{-1} (24-53 % of aboveground biomass or 20-35 % of total biomass: Malaisse and Strand 1973, Chidumayo 1993 1995, Malimbwi *et al.* 1994).

Woody plants make up 95 - 98 % of the aboveground biomass of undisturbed stands; grasses and herbs comprise the remainder (Martin 1974, Malaisse 1978a, Chidumayo 1993, Frost 1996). Aboveground herbaceous biomass in relatively undisturbed, mixed-aged stands of miombo is usually less than 2.0 Mg ha^{-1} (range of recorded values: 0.1-4.0 Mg ha^{-1}). On average, forbs make up about 30 % of this biomass, though this varies considerably among sites and between years. Herbaceous yield declines exponentially with increasing woody plant basal area, levelling off at a low value above 10 m^2 ha^{-1}, the approximate point where the tree canopy cover is complete.

The nutrient content of the foliage of miombo plants is generally low. The nitrogen content of mature leaves of non-nodulated canopy tree species is about 1.9 %, significantly lower than that of the few nodulated, N-fixing species: 2.7%. The average phosphorus level is 0.17 % P. Mature leaves of understorey species have higher average N and P concentrations than non-nodulated canopy species and higher average P concentrations than nodulated species: 3.0 % N and 0.26 % P (Frost in press). Grass nutritional quality is lower than that of woody leaves for much of the year,

1.3-2.2 N % during the early growing season, falling to 0.5-0.8 % during the early dry season. This is below the approximate level required to maintain grazing ungulates, and is a major constraint to livestock production in the region in the absence of supplementary feeding.

Nitrogen, phosphorus and other elements are withdrawn from the leaves of miombo trees as the leaves age (Ernst 1975). The concentrations of N and P in senescing leaves of canopy trees are respectively about 34 % and 23 % lower than those of mature leaves. This withdrawal reduces the quantity of nutrients being recycled and lowers litter quality. Despite this, the N and P content of litterfall is higher than in other tropical moist forests at equivalent levels of N and P flux in litterfall (Vitousek 1984). Estimated annual fluxes at two dry miombo sites amounted to 30-35 kg N ha^{-1} and 3.4-4.2 kg P ha^{-1}.

The quality of foliage as a resource for herbivores or decomposers is also influenced by the amount of structural carbohydrates and the concentrations of secondary chemical compounds. Lignin levels are surprisingly low, less than 8 % (Jachmann 1989, Mtambanengwe and Kirchmann 1995). The level of total polyphenols is variable, 0-19 %, with non-N fixing species having higher levels on average, 10.2 %, than N-fixing species, 6.8 % (Palo *et al.* 1993). The difference in polyphenol:N ratios is even greater. Since leaf chemistry is a factor influencing both consumption by herbivores and decomposition, a wider survey of the chemical composition of leaves is needed, both among species and within a species through time.

The generally low nutritional quality of foliage is reflected in the low biomass of both wild and domestic herbivores. On average, the biomass density of indigenous large herbivores in conservation areas in which miombo predominates is only about 20-30 % of that expected at the same mean annual rainfall in those African ecosystems with nutrient-rich soils. In the richer ecosystems large herbivore biomass increases with increasing mean annual rainfall (Coe *et al.* 1976, Bell 1982), whereas in miombo it declines. Much of the herbivore biomass is made up of large-bodied species such as elephant, buffalo and selective grazers such as Lichtenstein's hartebeest and sable and roan antelope. Specialist ungulate browsers are rare.

The level of consumption by large herbivores is low (about 1 % yr^{-1} of available browse: Martin 1974) and is generally less than the amount eaten by invertebrates, mainly lepidopteran larvae (2-4 % yr^{-1} of annual tree leaf production in normal years, see Frost 1996). Consumption by invertebrates is distributed differently in time and space from that by mammals. Invertebrates are active mainly in the wet season and feeding tends to be distributed more uniformly among preferred food plants at a site. There are also marked year-to-year differences in consumption, associated with periodic outbreaks of lepidoptera larvae (Malaisse-Mousset *et al.* 1970). In contrast, mammals are active throughout the year but, except for elephant, they feed on herbaceous and understorey plants rather than in the canopy. Feeding is also patchily distributed, due both to selectivity for plant species and parts, and to daily and seasonal movements of the animals. Selection of mature leaves by elephant in Malawi was significantly positively correlated with the sugar and mineral content of tree leaves, and negatively correlated with total polyphenol, lignin and steroidal saponin levels (Jachmann and Bell 1985, Jachmann 1989). The controls on invertebrate herbivory are not known, though secondary chemistry is likely also to be involved.

Large areas of woodland can be defoliated during insect outbreaks. This results in a temporary reduction in leaf area, though the plants rapidly produce a new flush of leaves, particularly if defoliation occurs during the early part of the growing season. Insect outbreaks also produce a pulsed flux of nutrients from trees to the litter layer in insect frass which may stimulate microbial decomposition.

Litter quality is important in regulating the rate of litter decay, though moisture availability is perhaps the overriding constraint. Nitrogen mineralization from litter is positively correlated with the initial N content and negatively correlated with C:N, cellulose:N and lignin:N ratios, among others (Mtambanengwe and Kirchmann 1995). Both litter decay rates and N mineralization are low during the dry season. At a wet miombo site in Zaire (1270 mm MAP) more than 90 % of leaf litter decayed within a year (Malaisse *et al.* 1975), compared with only about 60 % at a drier site (885 mm MAP: Swift *et al.* in prep.). Termites took much of the litter at the wet miombo site.

Organic matter levels in miombo soils are generally low. The average organic carbon content of A-horizon soils from 64 profiles in miombo woodland was 1.4 % (range: 0.3-3.8 %). Organic carbon levels in dambo grasslands are substantially higher: 8.0 %, range 1.1-21.8 %. Low organic matter is a consequence of several factors: a preponderance of low-activity clays; high soil temperatures; the frequent incidence of fire; and the abundance of termites (Trapnell *et al.* 1976, Jones 1989). Widespread foraging on litter by termites of the family Macrotermitinae, most of which is completely decomposed by cellulase-producing fungi in their mounds, is particularly important (Jones 1989).

The size, density and regularity of tall termitaria is one of the prominent features of miombo landscapes. Tall mounds made by *Macrotermes* species can occur at densities of up to 5 mounds ha^{-1}, covering about 8 % of the area (Malaisse 1973). At this density, the biomass of *Macrotermes* species alone may be as much as 46 kg DM ha^{-1}, outweighing other soil fauna groups except humivorous termites. The biomass of the latter has been estimated to be up to 61 kg ha^{-1} (Goffinet 1976). This high biomass of termites may be responsible for considerable emissions of methane (Zimmerman *et al.* 1982, but see Seiler *et al.* 1984). Considerable amounts of methane are likely also to be emitted from seasonally flooded dambo soils, while during the dry season miombo soils generally may be a sink for methane.

Termite mound soils have higher levels of total N, acid-extractable P and cations than surrounding soils (Watson 1977, Trapnell *et al*. 1976, Jones 1989), due to both the concentration in, and subsequent decomposition of, organic matter within the mounds (Jones 1989), and the concentration of minerals through the evaporation of soil water in chimneys within the mound (Weir 1973). This produces nutrient-rich patches within an otherwise nutrient-poor landscape. The termitaria, as a result, invariably support distinctively different vegetation from the surrounding woodlands (Malaisse 1978b), and are often the focus of activity for birds and other animals which might otherwise not do so well in such a largely unproductive environment. Termitarium soil is widely used by farmers as an amendment to their fields (Watson 1977).

Miombo is notable among dry tropical woodlands and forests for the number of tree species having ectomycorrhizae (ECM) rather than vesicular-arbuscular mycorrhizae (VAM) associations (Högberg 1982 1992, Högberg and Piearce 1986).

Most of the dominant tree species including species of *Brachystegia*, *Julbernardia*, *Isoberlinia* (Fabaceae: Caesalpinioideae), *Marquesia* and *Monotes* (Dipterocarpaceae) and *Uapaca* (Euphorbiaceae) have ectomycorrhizae. Fewer tree species in miombo have VAM, and only some of these are nodulated and so potentially fix nitrogen. In contrast, many of the dominant understorey shrubs and herbs are nodulated, particularly in regularly burnt communities. The dominance of ECM tree species in miombo may reflect the advantage that such species have on seasonally-dry infertile soils; the few other tropical ecosystems dominated by ECM tree species also occur on infertile soils (Högberg 1982). Ectomycorrhizae may be particularly important in enabling plants to take up nutrients direct from the litter. The mycorrhizae depend on carbon supplied by the host plant but the cost of maintenance to the plants has not been measured in miombo. It could be substantial.

Dry season fires are a regular and frequent feature of miombo ecosystems (Trapnell 1959), occurring at most sites at 1-3 yearly intervals. Fires in miombo probably constitute the single largest area burned in the world, around 1 million km^2 yr^{-1} (Scholes *et al.* 1996). Fire-return intervals depend on fuel accumulation rates, both at the site and in the surrounding vegetation, and on proximity to potential sources of ignition. Fires in the miombo region are an important source of trace gas emissions, methane, carbon monoxide and nitrous oxide (Scholes *et al.* 1996, Andreae *et al.* 1996). Most fires probably originate accidentally from people preparing land for cultivation, collecting honey, or making charcoal (Chidumayo 1995). Deliberate burning is done by hunters and livestock owners, to provide a green flush that attracts the animals. Fire is also used to clear areas around homesteads and alongside paths between settlements.

Fires in miombo are fuelled largely by grass and fine woody material, and their impact on plants depends on their intensity and timing in relation to plant phenology. Late dry season fires are more intense and destructive than fires occurring in the early dry season when fuel moisture contents are relatively high and ambient temperatures and windspeeds are low. Fuel load is largely a function of time since the last fire, the previous season's rainfall (which determines grass production), the amount of grazing and the extent of woody plant cover. Fires tend to be more frequent and intense in areas of low woodland cover and high mean annual rainfall, where grass production is high but where grass quality and therefore grazing pressure is low. Emission factors for trace emissions from these fires can vary by a factor of 6 to 8, depending on grass:woodland ratio (Ward *et al.* 1996).

Four functional groups of miombo plants are recognized in relation to their degree of tolerance to fire (Trapnell 1959, Lawton 1978): fire-intolerant, such as the forest species; fire-tender (including most of the dominant canopy species when young); and semi-tolerant and fire-tolerant species. Changes in fire frequency therefore change vegetation structure and composition. Frequent late dry season fires eventually transform woodland into open, tall grass savanna with only isolated, fire-tolerant canopy trees and scattered understorey trees and shrubs. In contrast, woody plants are favoured by both early burning and complete protection. Since grass biomass declines sharply as tree cover increases, a period without fire would lead to gradual tree canopy closure, the suppression of grass growth, and lower fuel loads. Lower fuel loads mean less intense fires, less damage to woody plants, uninterrupted woody regrowth and continued canopy closure.

Fire interacts with large herbivores in affecting vegetation structure (Guy 1989). Elephants are well known for their habit of ringbarking, breaking, pushing over and uprooting trees and shrubs (Thomson 1975). This transforms relatively dense woodlands into more open wooded grasslands with scattered tall trees, resprouting tree stumps, and a dense layer of low growing shrubs. The increased grass production leads to higher dry season fuel loads, more frequent and intense fires and further suppression of woody plants.

The dominant trend in regenerating miombo in the absence of frequent hot fires or other intense disturbances is therefore towards the development of woodland (Strang 1974). The trees are difficult to eradicate; most of the woody plants resprout vigorously from surviving stems and rootstocks. Only where the plants are thoroughly uprooted during disturbance are marked changes in composition likely. The dispersability and longevity of the seeds of *Brachystegia*, *Julbernardia* and most other Caesalpinioideae are low so that, where the trees are eliminated, recovery to the original state, at best, will be slow.

The dynamics of miombo woodlands have been interpreted largely in terms of a single-state equilibrium model of succession to a regional climax vegetation - dense woodland in drier regions and semi-evergreen or evergreen forest in wetter areas - with fire and disturbance by people or wildlife being the main processes reversing this trend (Freson *et al.* 1974, Strang 1974, Lawton 1978). For example, Freson *et al.* (1974) propose a three-stage regressive series (dense dry forest-open miombo woodland-savanna) induced by the combination of wood cutting and fire. The view that miombo is a sub-climax formation arises partly from observations of miombo juxtaposed with patches of evergreen forest where topography and soils seem superficially to be the same (*e.g.*, Lawton 1978). White (1983), however, notes that where evergreen forest occurs alongside wet miombo there is a transition to deeper soils, suggesting an edaphic control.

More recently, there have been attempts to describe miombo dynamics in terms of multi-state models in which, following abandonment of cultivated fields, or the combined impacts of elephants and fire, there is a transition either to open woodland dominated by *Combretum* spp. or to grassland (Stromgaard 1986, Starfield *et al.* 1993). Fire is considered to be the driving force behind the transitions. A longer than normal fire-free period is needed to return the vegetation to *Brachystegia*-dominated woodland.

Few studies of vegetation change in miombo have followed changes at a site over time. Most interpretations have been based instead on contemporaneous studies of the vegetation at a number of sites presumed to differ only in fire regime (Trapnell 1959, Lawton 1978, Chidumayo 1988) or time since abandonment of cultivation (Stromgaard 1986). Short-term studies in any event are unlikely to produce many insights, given that most of the tree species, including all the canopy dominants, are relatively long-lived (lifespans 60-120 years). Simulation models of plant community dynamics (*e.g.*, Desanker and Prentice 1994), supported by long-term monitoring of vegetation change at a range of sites, will be needed to predict vegetation change under existing and changed conditions.

Land Uses in Miombo

Human population densities over much of the miombo region are relatively low, averaging about 15 persons km^{-2} (range: 7-8 persons km^{-2} in Angola and Zambia to over 110 persons km^{-2} in Malawi), generally lower than those found in climatically similar areas elsewhere in Africa. Population growth rates are high, 2.5-3.5 % per annum, and although some of the increase in population is being absorbed by urbanization (bringing its own problems), the expanding populations mean greater demands on the land and its resources and changes in the kinds and intensities of land use.

There is considerable diversity in the ways people use miombo (Trapnell and Clothier 1937, Allan 1965, Puzo 1978). Apart from commercial farming (tobacco, maize, soya) and land set aside for wildlife conservation and tourism (national parks, safari areas and game reserves *etc.*) the main form of land use is small-scale sedentary and shifting cultivation of maize, cassava, small grains and pulses. Where present, dambos are used for growing cereals and root crops during the wet season, and for growing vegetables and grazing livestock during the dry season. The interfluves are used for cultivating rain-fed crops, wet-season grazing, and as the source of wood for fuel and construction, as well as of various non-timber forest products (NTFPs). Apart from the drier areas of Zimbabwe and Tanzania, there are relatively few livestock, many fewer than people would like to have. The reasons are complex. Low forage quality and animal diseases are major proximate constraints, themselves reflections of broader influences of climate, geology and soils (Bell 1982).

Many households depend on natural products derived from the surrounding woodlands and grasslands. These products include fuelwood, charcoal, timber, thatching grass, fibre, fruit, mushrooms, honey, edible caterpillars and other animals, organic inputs for fields, fodder for livestock, and many other items. At least 50 edible plant species are recorded from miombo (Malaisse 1978a). A number of cultural practices, largely unique to the miombo region in their extent, have developed in response to some of the prominent ecological features of miombo ecosystems. For example, the widespread traditions of bee-keeping, gathering mushrooms, and collecting edible caterpillars reflect, respectively, the dominance of prolific flowering entomophilous trees (Clauss 1992), the dominance of tree species with ectomycorrhizal associations, many of which produce edible mushrooms (Pegler and Piearce 1980), and periodic eruptions of some lepidoptera populations (Malaisse-Mousset *et al.* 1970).

The farmers use miombo landscapes in a fine-grained manner, exploiting localized patches of higher fertility and avoiding areas of particularly poor soils (Carter and Murwira 1995). Because of the low fertility of most of the soils, few areas, other than fertile alluvium in river valleys, can be cultivated continuously without a decline in fertility. Organic amendments (leaf litter, manure), termitarium soil, ash from burnt brush piles and, where available and affordable, inorganic fertilizers, are used to counter low and declining soil fertility (Swift *et al.* 1989, Carter and Murwira 1995). Shifting cultivation is carried out where there is enough land, though this is changing as population pressures increase (Chidumayo 1987a, Stromgaard 1989).

Slash-and-burn (ash-fertilization) agriculture in particular is widely practised in miombo. The practice appears well adapted to the generally infertile soils of miombo, particularly in the wetter regions where woody plant biomass is high and cut trees regenerate rapidly through resprouting. The best-known of these is the large-circle *chitemene* system practised by the Bemba people of northern Zambia and southeastern Zaire (Richards 1939, Allan 1965, Puzo 1978). In this system the foliage and outer branches of trees are cut from an outfield area and stacked in an infield area where they are left to dry before being burnt just prior to the annual rains. The outfield area is about 5-8 times larger than the infield area, which averages about 0.3 ha (range 0.02-1.03 ha). Traditionally, the trees are not stumped but are allowed to resprout before again being harvested about 25 years later (Chidumayo 1987a, Stromgaard 1988).

The plots to be chopped are selected on the amount of wood available for burning (Puzo 1978). By concentrating the brush into large piles, rather than spreading them over a wider area, farmers obtain a deeper ash bed and a greater fertilizing effect through the release of plant nutrients and increases in soil pH (Stromgaard 1984, Mapiki 1988, Araki 1992). A deeper ash bed reduces the amount of soil tillage required, an advantage to farmers who have no livestock, while the greater fertility contributes to larger crop yields. This means that the plots to be cultivated can be smaller and more manageable. More brush also means a hotter fire, more complete combustion of the plant material, and the suppression of weeds during the first few years of cultivation. The land is cultivated until the added fertility is exhausted or until the regenerating woody vegetation and weeds make continued cultivation unproductive. The plot is then abandoned to a long fallow period and new fields are opened up (Puzo 1978).

Various other forms of shifting cultivation occur within the region. Some are variants of the *chitemene* system described above, others involve short-rotation fallows. On inherently infertile soils, a long fallow period is necessary for replenishment of both the vegetation and soil nutrients. With the ongoing expansion of the human population in the region, leading to a reduction in the area of uncultivated land, fallow periods are becoming shorter and shifting cultivation is gradually being replaced by more permanent agriculture (Lawton 1982, Chidumayo 1987a, Stromgaard 1989). As the duration of the fallow declines, trees are felled rather than lopped to produce sufficient biomass to burn and fertilize the soil, reducing subsequent fallows to a fire-maintained wooded grassland called *chipya*. Eventually, most of the potentially arable land is cultivated more-or-less permanently. In the absence of more intensive soil fertility management, this is likely to result in a gradual and long-lasting decline in fertility.

Shifting cultivation is often viewed as an early stage in agricultural development, conditioned by low population densities (and therefore plenty of uncultivated land and no incentive to develop more intensive methods of farming) and limited technology. In miombo, this argument is extended to cover the impact of tsetse fly, mainly *Glossina morsitans*, the vector of the protozoan blood parasites, *Trypanosoma* spp., that cause trypanosomiasis ('sleeping sickness' in humans, *nagana* among domestic livestock). The threat posed by trypanosomiasis is thought to prevent people from keeping domestic livestock, particularly cattle and donkeys, leading to shortages of animal draught power and manure for fertilizing the fields, inefficient hand-cultivation of small plots, rapid exhaustion of the soil, and early abandonment in favour of virgin woodland elsewhere.

At best, this is a gross oversimplification of the complexities involved in the development and practice of shifting agriculture. Richards (1985) has cautioned against viewing shifting cultivation as a single, undifferentiated system of farming, distinct from permanent cultivation, for example. Instead, it should be seen to constitute a range of actions, among a wider array of land-use practices, each used according to particular ecological and economic circumstances. Given the low nutrient status and high acidity of the soils it is perhaps more appropriate to view *chitemene* as well-adapted strategy of ash-fertilization that makes use of the inherent capacity of the plants to resprout when cut, and which allows people with limited resources to overcome the constraints of their environment through capitalizing on the nutrients stored in the vegetation.

The presence of tsetse fly undoubtedly has affected human ecology in miombo, but not necessarily in the way and to the extent commonly assumed. The presence of tsetse fly and the threat of trypanosomiasis seems to have determined pre-colonial settlement patterns and densities. For example, in south-eastern Tanzania, people lived in small isolated settlements, minimizing the risk of infection by human trypanosomiasis (Matzke 1979). People responded to outbreaks of sleeping sickness by abandoning the affected areas and dispersing to new settlements at lower densities. The alternative response, widely promoted by colonial authorities, was to consolidate people into large enough concentrations to clear and keep open the surrounding bush thereby destroying tsetse fly habitat in a sufficient radius around the settlement and associated agricultural lands (Matzke 1979). This was possible in drier areas but has proved difficult to sustain in wetter regions where tree regrowth rates are high and the soils too infertile to be able to support the local density of people needed to keep the vegetation open (Matzke 1979). The presence of tsetse fly still governs aspects of agricultural, veterinary and development policies in the region. Attempts to rid miombo of tsetse fly through bush-clearing, eradication of wildlife, ground- and aerial-spraying of insecticides, and the use of insecticide-impregnated, odour-baited 'targets', have all had, and continue to have, an impact on land use and land cover across large areas of miombo.

Land use in miombo therefore reflects a range of adaptations by farmers to the intrinsic constraints and opportunities of climate, landscapes, soils, vegetation, animals, pests and disease. Many of the adaptations, however, have developed under different socio-economic and demographic circumstances from those prevailing today, and are becoming increasingly difficult to sustain as populations increase and the demand for agricultural land intensifies. Population growth, however, is not the only, nor necessarily the main, cause of pressure on natural resources. Superimposed on a largely inherently infertile environment are inequalities in land distribution, unsecured tenure, deteriorating economic circumstances, lack of credit, technical advances in disease-control and agricultural production, commoditization of agriculture, declining terms of trade among less developed countries on world trade markets, increasing commercialization of natural products, and frequent droughts.

Individually and interactively, these factors are affecting the patterns of land-use and productivity. Large areas of woodland have been, and continue to be, modified or transformed by people. The changes include reductions in tree density due to frequent harvesting for fuelwood, charcoal production, construction material, and slash for burning and fertilizing fields, declines in woodland cover due to frequent burning, and conversion to permanently cultivated land or, to a much lesser extent,

plantations of fast-growing non-miombo trees. These changes in land cover and ecological functioning have long-term socio-economic impacts (such as reductions in the availability of NTFPs, less forage for livestock, and fewer inputs to sustain the fertility of increasingly large areas of arable land), as well as a range of environmental impacts affecting ecological functioning, carbon storage, trace gas emissions, hydrology and regional climate (Justice *et al.* 1994 [IGBP Report 31]). This programme is aimed at understanding these impacts and their consequences.

Key Issues in the IGBP Miombo Network

At the Miombo Intercore Project Meeting in Zomba, key issues for a miombo global change research initiative were identified. These were formulated into a series of research questions and hypotheses which are presented below.

What are the Current Directions and Rates of Change in Land Use and Land Cover?

Human activities are central to the current dynamics of miombo ecosystems. The extensive and intensive use of the soils and vegetation by agrarian communities has undoubtedly shaped, and continues to shape, much of the present miombo landscape. The details, however, have still to be fully revealed and understood. Much of the available data is descriptive rather than analytical; collected in different ways, making comparisons difficult; short-term, so that lagged feedbacks are not apparent; and focused either at the micro-scale, with extreme emphasis on local detail, or at a regional or larger scale, where the data are so aggregated and generalized that the underlying processes are difficult to discern.

There is therefore an urgent need to link the findings of site-, time-, and circumstance-specific case studies with the broader findings of regional studies of land-use and land-cover change. A more systematic approach is required that aims to understand which details of human circumstances, knowledge, perceptions, motives, actions and responses, so apparent at a local scale, emerge as pattern and influence processes at a larger scale. Moreover, because the circumstances are not static, the focus of research must shift from descriptions of pattern to studies of processes.

- What are the present patterns of land use in miombo, and what are their historical, socio-economic and environmental determinants?
- To what extent, in what ways, and at what rates are the patterns of land use changing, and why?

- What are the external driving forces and internal modifiers of the changes in land use and land cover?
- What are the effects on land use of current macroeconomic policies, and of sectoral policies on agriculture, forestry and conservation?
- Can the location and rates of future land use change be predicted?
- How are these changes altering the attributes of different land cover types and their spatial patterns (sizes, shapes, contiguity and connectivity)?

One hypothesis is that traditional land use practices are governed by the constraints of infertile soils, inadequate draught power (due to a shortage of livestock because of poor-quality grazing and the prevalence of animal diseases), and limited markets for produce. These constraints are currently being alleviated through a wider use of fertilizers and cattle feed supplements, the control of disease, and improvements in infrastructure, coupled with a rapidly-growing population and political stabilization in southern Africa. The prediction is that these developments will lead in turn to massive changes in land use and land cover throughout the miombo region in the coming decades. The process is already observable in countries such as Malawi and Zimbabwe. The rapid conversion of large areas of *cerrado* in Brazil to crop lands during the 1980s illustrates the speed with which the process can occur once constraints are removed.

Other important issues relate to the human dimensions of land use and resource allocation in this important and sensitive region. Transnational and internal demographic factors, most notably migration, must be considered part of the research. In addition, broad issues which relate land use practices to cultural attributes on the one hand and market forces on the other must be considered in terms of understanding the current and future trajectories of land use and cover change in Miombo. For instance one hypothesis is that strong culturally-endowed land use practices limit peasant involvement in market economies; that African peasants deliberately refuse to be captured by the market economy (Hyden 1980). The rapid commercialization of natural products in Zimbabwe and elsewhere in recent years (Campbell 1996) suggests otherwise. Finally the tenet that land-use intensification cannot take place in this region must be examined critically.

What are the Consequences of Land-Use and Land-Cover Change?

Changes in land use and land cover in miombo potentially affect a wide range of socio-economic and environmental processes. Reductions in the area of uncultivated woodlands may reduce the availability of fuel wood, construction material, and non-timber forest products; diminish the area of communal grazing land; and adversely affect the free ecological services provided by trees. Such impacts may fall disproportionately on the poorest members of society, worsening their socio-economic circumstances. Reductions in tree canopy cover can adversely affect local, and possibly regional, climates through effects on albedo, air temperatures and relative humidity (Malaisse 1978a), while the reduced leaf area means lower evapotranspiration rates, greater recharge of groundwater, and changes in hydrological functioning downstream (McFarlane and Whitlow 1990). Conversion to permanently cropped land, in the absence of intensive soil management, can lead to reductions in soil organic matter, nutrient depletion, and soil erosion. In all cases, changes in the kinds and rates of emission of trace gases can be expected.

Regional Climate

The land surface, and in particular vegetation, regulates the partitioning of radiant energy into different components. This partitioning is an important boundary condition for the climate system at all scales. Changes in land surface properties will result in changes in energy partitioning, and hence in climate. The land surface is also important for climate as it is a major potential source of radiatively reflective particulates and radiatively active trace gases such as CO_2 and methane. Complex feedbacks exist between the land surface and climate which operate through both the hydrological and carbon cycles.

Processes that influence surface albedo are reviewed by Henderson-Sellers and Wilson (1983). In general, human-induced land-use changes tend to increase albedo, resulting in more energy being reflected back into the atmosphere. It has been suggested that this contributes to warming of the upper troposphere, which in turn leads to greater atmospheric stability and less convective rainfall (Shukla *et al.* 1990). Gornitz (1985, 1987) reconstructed land use changes in West Africa from historical records, censuses, atlases and descriptive reports and calculated changes in albedo due to alterations in land use. He concluded that evidence for apparent desiccation or 'desert creep' ('desertification') may be attributed, in large part, to adverse changes in soil and stream hydrology caused by anthropogenic disruption of the vegetation cover (Gornitz 1985). There are many counteracting factors to take into account when predicting how land-use changes might affect climate. Therefore, it is important to document the details of land cover and reconstruct its dynamics to analyze the effects of changes on the fluxes of energy and water, and how these in turn will affect climate.

- What are the phenological characteristics, physical features (plant height, density, cover, leaf area and distribution) and surface attributes (albedo, surface roughness, canopy conductance) of different land cover types in miombo?

- In what ways do these features influence soil-vegetation-atmosphere interactions?
- What is the impact of widespread, frequent fires on surface albedo, energy and water balance, and surface roughness?
- What effects do interannual climate variability have on land use, soil-vegetation-atmospheric interactions and the frequency of fire?

Water Resources

The headwaters of several major southern and Central African river systems lie in the miombo region. These rivers, on which many people depend, include the Zambezi, Kafue, Save, Okavango, Ruaha, Rufiji, Rovuma Lualaba, and Zaire. Changes in land cover are likely to have a variety of impacts on the total amount of water reaching these rivers, the timing of discharge, and on water quality (especially sediment and nutrient contents). For example, reductions in tree canopy cover on interfluves has been shown to increase annual streamflow in the upper Kafue River (Mumeka 1986), while augmented groundwater flow has been implicated in faster rates of subaerial erosion of dambos (McFarlane and Whitlow 1990).

- In what ways, and to what extent, do changes in land use and land cover affect local, landscape and regional hydrological processes?
- What is the relationship between land use and mass transport of the products of interfluve erosion, and what is the impact on water storage capacity downstream?
- What effects will these changes have on the availability and quality of both surface and subsurface water resources?
- What is the impact of more intensive land use of wetlands, particularly *dambos*?
- In what ways might changes in climate, including changes in rainfall variability, affect patterns of land use, water storage, and water quality?

Carbon Storage and Trace Gas Emissions

The wide extent of miombo means that land use change in the region could have globally-significant impacts. Miombo landscapes are the main source of the cloud of tropospheric ozone which drifts off Africa every September (Fishman *et al.* 1991), and are the source of about 10% of the global carbon monoxide and biomass-burning aerosol particle budgets (Scholes *et al.* 1996a). Detailed analyses of tropospheric ozone over southern Africa are given in Thompson *et al.* (1996a and 1996b). The miombo woodlands are also significant sources of nitric oxide from biogenic processes in the soil; methane from the dambo wetlands, ruminants and termites; and non-methane hydrocarbons from the vegetation.

Mature miombo woodlands contain about 95-136 Mg C ha^{-1} in the vegetation and soil, depending on climate. Conversion of these woodlands to short-duration crop agriculture would release large amounts of carbon dioxide to the atmosphere, perhaps as much as 50 Mg C ha^{-1}, or about 14 Pg C if the entire miombo region were to be converted. This is a potentially large contribution in relation to the current annual global flux due to land use change of about 1.6 Pg C yr^{-1} (IPCC 1996). On the other hand, if miombo woodlands were managed to maximize carbon storage, a substantial quantity of carbon could be sequestered in biomass, soils and woodland products.

- What are the major trace-gas fluxes between miombo ecosystems and the atmosphere, and how do these differ among the various land-cover types?
- What are the controls on these fluxes?
- What effects do changes in land use and land cover have on the flux of trace gases, both during conversion and afterwards?
- What are the types and amounts and geographic distribution of trace-gas emissions from different kinds of biomass fires (wildfires, slash-and-burn, hearth fires, charcoal fires), and what is their interannual variability?
- What are the residual (post-fire) effects of wildfires on the exchange of trace gases among soils, vegetation, and the atmosphere?

Natural Resources

The principle natural resources derived from miombo woodlands are not reflected in the formal economy. They consist of fuelwood and charcoal, essential for household energy for millions of people; fruit and other foods - honey, edible fungi, edible caterpillars, rodents and other small animals; timber for house construction; thatching grass; and wood and fibre for making household implements, baskets and other handicrafts. Rainfall in the miombo area is variable, resulting in periodic food shortages. On these occasions, the availability of wild foods, as well as other natural products that can be harvested and sold or exchanged for food, can be crucial to survival. These products also supplement peoples' livelihoods and diets during high-production years.

- What are the present trends in the use of natural resources of miombo?
- What impacts are present policies on land use (agriculture, forestry, conservation), agricultural credit, pricing and marketing, and economic structural adjustment, having on the resource-use practices at local and regional scales? What would be the potential impact of major changes in these policies?
- What is the impact of commercialization on the patterns of resource use?
- What are the key ecological processes sustaining production in miombo ecosystems and how are these being affected by land-use change?

- In what ways are changes in land use affecting the kinds and availability of natural products?
- To what extent are these changes affecting the patterns and intensities of use of these resources?

What Controls the Distribution of Miombo Species and Ecosystems?

The ability to understand the course of ecological change and to predict its longer-term consequences depends greatly on the level of understanding of how a particular ecosystem functions and what controls the distribution and abundance of key species. Miombo forms one of the major ecosystem types in Africa, occurring over a wide climatic range and a somewhat narrower range of soils, yet still displaying a relatively sharp transition to other major formations. Any Dynamic Global Vegetation Model (DGVM) must be able to predict the current extent of miombo if it is to be useful in predicting the consequences of future climate change. Existing DGVMs have been developed from a north-temperate perspective and are largely untested for major tropical formations. Similarly there is a need for such models to incorporate land-use practices (*e.g.* the use of fire) as an integrated ecosystem process.

A working hypothesis is that the distribution of miombo ecosystems is controlled by four factors: warm temperatures; moderate rainfall; a marked dry season; and infertile soils. The present biophysical boundaries of miombo are considered to be determined by climatic factors and soil fertility as follows:

- The upper altitudinal limit and possibly the southern geographical limit of miombo is controlled by low temperature (~-4 ^{o}C absolute mean minimum temperature: Ernst 1971)
- There is a lower limit to the length of the dry season (~4 months) below which either the trees are evergreen and form a closed canopy, precluding fire, or the soil is permanently saturated and supports hydromorphic grasslands and swamp forest
- There is a lower limit to water availability (700-1500 mm yr^{-1} and a minimum of 90-100 days growth opportunity annually) below which trees belonging to the Caesalpinioideae are replaced by more arid-adapted groups
- There is an upper limit to soil fertility, primarily in terms of P availability and possibly pH, above which miombo species are outcompeted by faster growing species characteristic of *Acacia*-dominated savannas.

The distribution of the key miombo species is likely to be controlled by a similar combination of climatic and edaphic factors.

What Controls Primary Production in Miombo Ecosystems?

The working hypothesis is that primary production in miombo ecosystems is broadly related to rainfall, but is everywhere strongly constrained by nutrient availability, particularly nitrogen and phosphorus. The relative importance of these two elements, and the extent to which they interact in their effects on miombo production, is not fully known. Because primary production underpins both the natural resource potential of miombo and its potential for absorbing or emitting greenhouse gases, the question of the controls on primary production is of fundamental importance.

The structure and composition of miombo woodlands, and hence its production potential, is also affected by disturbances such as fire and the felling of trees by people or elephants. These disturbances in turn affect the availability of water and nutrients, often positively. The nature of the interactions between climate, disturbance, structure, composition and function need to be explored more systematically, not least because they probably hold the key to understanding how miombo species and systems will respond to changes in global climate.

Core Experiments, Activities and Tasks

The proposed research on miombo is partitioned into seven core experiments and a set of integrating activities that cut across the core experiments. The order in which they are listed does not reflect any particular priority. The approach taken begins with analyses of the character and dynamics of land use and cover change, which is then tied to its ecological effects. In essence, the approach described below first defines the causes of land use and cover change, and then its consequences in ecological terms.

It is recognized that there will also be significant social, institutional and economic consequences to changing land use patterns in the region, and this component will be developed at a later point through close collaboration with the appropriate Programme Elements of the IHDP, such as its emerging Institutions Project. However, since the program structure of the IHDP is in its formative stages, this report focuses the discussion of consequences of LUCC in biophysical terms.

The first two Core Experiments define an approach which is parallel to Focus 1 and Focus 2 of the LUCC Science Plan (Turner *et al.* 1995 [IGBP Report 35/HDP Report 7]). The approach articulated in this document heavily emphasizes Focus 2 of LUCC, which is oriented around direct observations and empirical models. This approach, which could be called "pattern to process", begins with analyses of the spatial and temporal characteristics of LUCC in the region, and then, through case studies, attempts to define the underlying processes at various scales which give rise to the patterns observed. Further refinement of the science plan is expected, and in doing so the Core research activities would expand the work of Focus 1 through more detailed case studies.

Core Experiment 1: Land Use Dynamics

Case studies, along with spatial analyses from direct observation (Core Experiment 2) can be used to build sets of micro- and meso-level models of land-use and land-cover change through time. The goals of such an approach are both description and explanation in the form of useful causal understanding (Clark *et al.* 1979).

The aim of this experiment is to develop and test hypotheses regarding the controls on land use in the miombo region. The complexity of the problem deepens with the understanding that three dimensions of drivers - socio-economic, biophysical, and land management (proximate causes) - are relevant to land-use/cover change, two of which involve adaptive agents and systems that respond to and sometimes anticipate changes in the other spheres. Global change modellers have only recently begun to deal with this problem with regard even to biotic feedbacks (Baskin 1993). An approach that integrates the three spheres, therefore, is not only necessary, it is forward looking.

The approach will consider the multiple ways in which land cover and human activity interact. It can change as a result of: (i) independent changes in biophysical drivers (*e.g.,* climate and atmospheric change); (ii) direct alteration (*e.g.,* deforestation); (iii) indirectly mediated through the biophysical processes (*e.g.,* groundwater withdrawal leading to a lowered water table and to reduced stream flow and altered vegetation); or (iv) a more complex chain of human activity, which feeds back to human activity, which then directly alters land cover (*e.g.,* human introduction of rinderpest, change in wild herbivore population, advance of woodland with tsetse, leading ultimately to mechanized clearing, see Sinclair 1979).

There are two steps to disaggregating this problem of multiple factors. The first is to divide forcing functions into social and biophysical drivers and proximal drivers. The second is to analyse each set of drivers in terms of spatial and temporal scale in an attempt to resolve at least some of the complexity and controversy regarding multiple driving forces. This step draws on Holling's argument that the dynamic behaviour of many ecological systems can be explained by a few driving forces operating at characteristic frequencies and spatial scales - the extended keystone hypothesis (Holling 1992).

Available data (mostly descriptive) will be collated and new data collected. These data will be used to discern underlying processes of land-use change at the regional scale. Land-use change models will be constructed and will include factors such as biophysical suitability of broad areas for various land uses; trends in regional and global economics and trade; and regional demographic trends. Results from this experiment will be used along with land-cover change information from the Land Cover Dynamics Experiment to develop an understanding of how land-cover changes are driven by land-use changes.

The kinds of questions which will be emphasized relate to the spatial and temporal dynamics of land use and cover change, in particular investigating what controls the interannual variability of land-use changes as well as its spatial pattern over time. The research will consider such questions as: (a) are the inter-annual dynamics and rates of land conversion and abandonment to secondary forest significantly different from the decadal mean trends; and (b) through the integration of socio-economic

and satellite data and the development of dynamic LUCC models, can we improve our understanding of the dynamics of LUCC and the various controls (proximate and distant determinants) on rates of conversion and regrowth and land use transition sequences?

Activity 1 Microscale Land Use Case Studies

Case studies will document important factors for major current land-use systems such as shifting cultivation, slash-and-burn systems, modern village-scale agriculture, cash-economy agriculture, and government land use (forest reserves, national parks, plantations). Studies will also document patterns of land use in areas constrained by major pests and disease, such as the tsetse fly and sleeping sickness. Some of these data exist in the region, and will be collated and evaluated.

Task 1 Case Studies of Specific Land-Use Systems, Communities and Cultures

Activity 2 Historical Land-Use Patterns

The purpose of this activity is to build datasets for the development and testing of models. These will be reconstructed from archaeological and written records for the period 5000 to 20 years ago. Recent data will rely heavily on remote sensing products and regional/global data sets developed by various agencies such as FAO, CIESIN, World Bank, and national archives.

Task 1 Reconstruction of Land Cover and Land-Use Over the Last 300 Years

Task 2 Development of Spatial Database of Land Use and Socio-Economic Drivers

Task 3 Archaeological and Historical Studies of Land-Use Patterns

Activity 3 Regional Land-Use Change Modelling

The current distribution of land cover, recent trends in land use change when combined with existing socio-economic data bases and trends can be used to model potential changes of land cover and land-use change under different scenarios of population, economy and climate change. In the miombo region there are several relatively small-scale studies (*e.g.,* Scudder *et al.* 1982, Kalipeni *et al.* 1988) which can form the basic platform for creating a model for the entire region. Scudder has studied one area over a 30+year period, while Kalipeni *et al.* have documented a case study of the rural communities supporting a major city. Other case studies exist. Information like these is invaluable for looking at human dimensions of land cover change. The main purpose is to build a predictive model of land use change that will capture our current understanding of land-use systems in the region. The model will be used to develop scenarios for the immediate future given population and socio-economic projections.

The causes of land- cover conversion have often been attributed to such things as population growth, road building, and a host of other similar monotonically varying phenomena. Although population and infrastructure are important long term determinants of general trends over decades, interannual variability is not tightly linked to such parameters. Econometric variables such as variations in price structures and local market demands are likely to be better predictors of deforestation and abandonment rates over short time cycles. It is possible to couple satellite-based LUCC datasets to socio-economic data to build diagnostic models of the LUCC process.

Such models could provide: (a) an improved understanding of the factors which control variations in LUCC rates annually; (b) an improved understanding of the factors which determine the rate of secondary fallow woodland clearing; and (c) an improved understanding of the factors which control the balance between deforestation (the bringing of land into production) and abandonment (the taking of land out of production).

It is possible to develop models at two levels. The first are models based at Case Study sites and focused on establishing the critical village-level variables, dynamics and proximate determinants. The second level of model analysis could be developed at the scale of countries or the region. The Case Studies can be used to calibrate the regional model and provide a basis and location for validation of regional results.

Task 1 Develop Multiscale Model of Land-Use Dynamics

Task 2 Develop Scenarios of Land Use and Land Cover for Next 30 Years

Core Experiment 2: Land Cover Dynamics

Activity 1 Land Cover Change Mapping and Analysis

Recent developments through the NASA Landsat Pathfinder Program have shown that large regions of tropical forest can be mapped using high resolution satellite data to provide the basis for carbon balance studies and natural resource management (Skole and Tucker 1993). Time-series satellite data over the last twenty years are used to derive the location, extent and rates of deforestation. Similar base maps are now needed for the miombo region. Due to the strong seasonality and interannual variability of vegetation of the miombo system there is the need to augment the Pathfinder approach to ensure selection of the optimum period for discrimination of the desired land cover types and to enable interannual comparisons. This proposed activity would provide a pilot study to evaluate the synergistic use of time-series coarse resolution and temporal samples of high resolution data. The activity would also need to match the components of the miombo system that can be mapped using these complimentary data types with the vegetation classes required by the miombo scientists. During this pilot study period it will be important to ascertain the current status of land cover mapping within the miombo region and identify any recent developments using satellite data to map vegetation and vegetation change. For example, the current status and plans of the United Nations/Food and Agricultural Organization (UN/FAO) Africover Project, World Bank Resource Inventory Mapping Project (Zimbabwe) (REIMP) project, the FAO 2000 Tropical Forest Assessment, the Zimap/SPOT national image mapping project are complementary projects already identified which will involve various national forestry and mapping agencies within the region. Close coordination is desirable with such ongoing land cover mapping projects.

Research is underway towards the development of new and improved techniques for surface parameterization using existing and planned satellite remote sensing systems *e.g.,* Running *et al.* (1995). There will be a considerable advantage to having the IGBP Transects provide a test bed for developing and testing these algorithms. For example, involvement of miombo scientists in the evaluation of these resulting data sets would help ensure the applicability of the methods to the miombo environment and an early access to improved data sets. It is quite feasible that a series of satellite product validation campaigns could be organized within the region underpinned by a strong ground measurement program. Within NASA's Earth Observing System (EOS) there is currently discussion of a potential regional miombo validation campaign following the launch of the EOS AM platform.

Task 1 High Resolution Satellite Mapping of the Miombo Region

Following the pilot studies an implementation plan will be developed for a comprehensive mapping of the entire miombo region using up-to-date high resolution imagery. Emphasis will be given to having in-country expertise closely involved in the image interpretation. The interpreted image data planes could be entered into a Geographic Information System (GIS), mosaiced, registered and mapped to a coordinate system appropriate for the region, following the Landsat Pathfinder approach (Skole and Tucker 1993). The main product will be a spatially explicit data base for the mid 1990s.

Task 2 Determination of Optimum Procedure for Mapping the Rates of Land Cover Change in Miombo

Since the availability of high resolution satellite data in the early 1970's, demonstration studies have been undertaken using Landsat data for monitoring land cover change in the miombo environment. These studies have focused on individual study sites and intensive image analysis techniques. With the increasing availability of high resolution data for global change research and the extension of the time-series to a twenty year record, there is an interest to provide a comprehensive quantification of the rates of land use change within the region. Techniques that have been developed for humid tropical forests now need to be refined for monitoring seasonal vegetation. A pilot study will be developed to determine the optimum procedure for quantifying and mapping the rates of land cover change between the 1970's, 1980's and the recent baseline data. The results will be used to develop a spatially explicit data base of the rates of change over the twenty year Landsat record.

Task 3 Evaluation of the IGBP DIS 1 km Land Cover Product

The IGBP-DIS 1km Land Cover product for the region will be evaluated and refined to meet the coarse resolution data needs of the regional science community. The IGBP 1km Land Cover Product is currently being developed by the Eros Data Center (Sioux Falls, USA) and the EC Joint Research Center (Ispra , Italy) preliminary classifications of the region will be available in 1996. The classification scheme is based on an unsupervised classification approach applied to the IGBP Global 1km Product (Townshend *et al.* 1995). Ancillary data are used to group the clustered classes according to the functional vegetation categories identified by the Land Cover Working Group (Belward and Loveland 1995, Running *et al.* 1994). Local expertise will provide an important first order validation of this segment of the global product and to suggest improvements to the interpreted data base.

Task 4 Evaluation of Satellite Methods for Direct Parameterization of Tree Density

Various methods are currently being developed to derive information concerning the mixture of trees and grass on Land Remote-Sensing Satellite (Landsat) and Advanced Very High Resolution Radiometer (AVHRR) imagery. For example a regional database depicting tree cover amounts derived from 1km AVHRR data is currently being generated at the Geography Department of the University of Maryland (USA) using mixture modelling techniques. Involvement of miombo scientists in evaluating such remote land surface parameterizations is highly desirable.

Activity 2 The Timing, Distribution and Area Extent of Fire in Miombo

Fire is an important indicator of ecosystem disturbance. Recent studies using AVHRR 1km and Defence Mapping and Satellite Photographs (DMSP) satellite data for southern Africa have shown extensive burning in the miombo region (Figure 3). The contribution of fire in the region in terms of continental trace gas and particulate emissions is starting to be quantified (Scholes *et al.* 1996a and 1996b). The Miombo Initiative would benefit from the availability of a regional data base of fire timing and distribution as an input to the regional ecosystem process modelling.

An activity currently being developed by the IGBP-DIS Fire Algorithm Working Group is to make available the existing regional fire data sets to the IGBP science community. A close relationship between the IGBP-DIS Fire group and the miombo scientists would provide an enhanced validation of these regional fire data sets. The IGBP-DIS Fire Group will be generating a global fire product within the next 18 months.

Task 1 Validation of IGBP-DIS Fire Product for the Region

Planned controlled burns within the miombo region as part of experiments on miombo will be used for satellite fire algorithm validation. Such burns could be organized where appropriate in conjunction with fire process studies, similar to the approach developed in the Biomass Burning Experiment (BIBEX) SAFARI Campaign (Andreae 1994). Such validation activities also give miombo scientists a better perspective on the accuracy and utility of the IGBP-DIS Fire product for the region.

Task 2 Direct Measurement of Annual Area Burned Using Satellite Data

This task will be developed around the IGBP-DIS 1km AVHRR data base to generate a direct measure of annual area burned for the miombo region from satellite data. The approach being developed by the remote sensing research community uses the 1km AVHRR daily time series to track the evolution of burn scars within the miombo landscape. An important component of this activity will be validation.

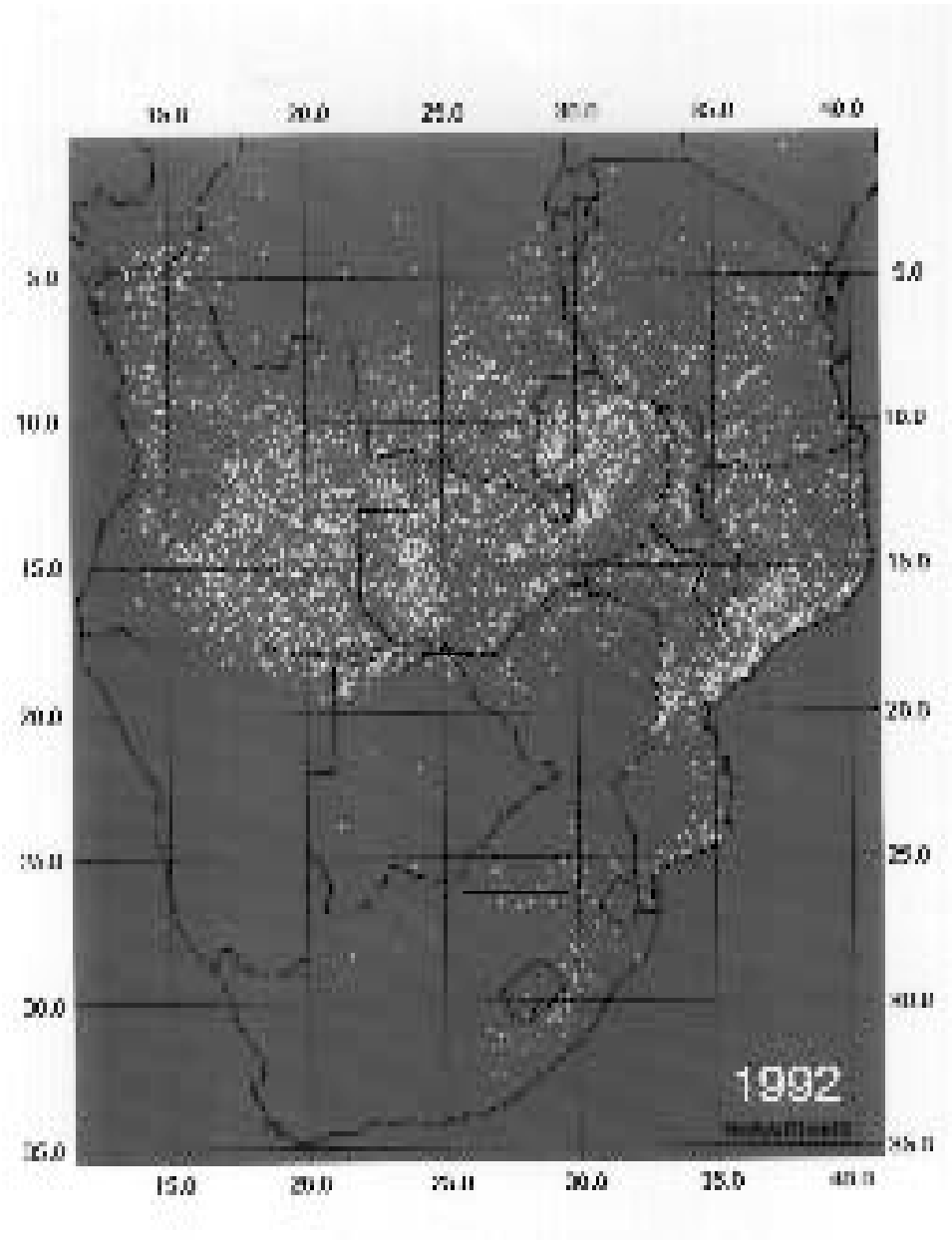
Activity 3 Landscape Patterns and Processes

The aim is to understand and predict the consequences of land cover changes for the flow of ecosystem goods and services (such as plant products, water yield, biodiversity) from miombo landscapes. Deforestation is widely perceived to be a priority issue throughout the miombo region. The most widely ascribed effects of deforestation are depletion or outright loss of potentially valuable resources (wood, fodder, fruits and other non-timber forest products); increased run-off, erosion and siltation; disruption of hydrological regimes; fragmentation of habitats; and loss of biodiversity. More subtle effects include reductions in carbon storage, a potentially significant factor in global climate change; redistribution of water, soil and nutrients within watersheds; spatial reorganization and homogenization of vegetation mosaics; changes in albedo, surface energy budgets and local microclimates; and changes in biogeochemical cycling and the flux of energy and nutrients among ecosystem compartments (Lambin 1994).

Although it is often implied that deforestation constitutes environmental degradation, this is not necessarily the case. At least initially, people usually derive a net benefit in terms of opening up new land for agriculture and increased access to, and extraction of, resources. Nevertheless, diversity, productivity and environmental quality often eventually decline, posing a number of questions. Under what circumstances do these contrasting outcomes arise? To what extent are the outcomes determined by the environment of a site (*e.g.,* climate, soils, topography, vegetation) as opposed to socio-economic features (*e.g.,* management, tenure, technology, information)? Do small initial changes become self-amplified, destabilising the soils and vegetation to a point of irreversible change, or are there processes which function to stabilize the changes? If so, in either case, what are the processes and circumstances leading to these outcomes?

Figure 3

Composite of sub-pixel high temperature sources (active fires) derived from daily NOAA-AVHRR 1-km satellite data from August through October 1992. (NASA/GIMMS).



The following tasks will attempt to understand the consequences of land cover changes on ecosystem processes at the landscape level. This will be accomplished by quantifying the spatial organization of vegetation and soil surface features in deforested and intact landscapes; by relating the spatial organization of the landscape elements and the processes determining them to variations in climate, soil types, topography, and land management. Models will be developed to study the temporal changes in deforestation and the effects on landscape patterns, and ecosystem processes and function.

Task 1 Spatial Analysis of Miombo Landscape Units and Processes

Task 2 Development of Models of Deforestation

Task 3 Modelling Effects of Deforestation on Landscape Patterns

Box 2

Satellite Data Availability for the Region.

Remotely sensed satellite data will play a major role in the regional project. The data can be used to parameterize or validate models as well as providing a twenty-year record of land cover change in the region. The miombo region is within the coverage of the South African Receiving Station at Hartesbeesthoek. From the early 1980's, coverage of the region by Landsat, Système pour l´Observation de la Terre (SPOT) and AVHRR data has been extensive and a systematic archive has been developed. An IGBP-DIS data rescue activity is currently underway to secure the South African Landsat Multispectral Scanner System (MSS) archive for the region which is in danger of being lost. Additional Landsat data from the early 1970's are available from the US National Landsat Archive at the Eros Data Center, Sioux Falls, South Dakota. In addition IGBP-DIS has been securing and archiving daily 1km data for the region since April 1992 (Townshend *et al*. 1995, Eidenshink and Faundeen 1994). The high cost of high resolution satellite data has long been an obstacle for the use of the data for regional studies by the science community. The IGBP-DIS High Resolution Project is aimed at reducing this obstacle by arranging with the data providers such as NASA and the Centre National d´Etudes Spatiales (CNES), for the provision of low-cost high-resolution satellite data for the IGBP research community (IGBP Report 30). The Miombo Network could benefit from participation in this project and the early identification of the satellite data needs for the project.

Core Experiment 3: Ecosystem Dynamics and Disturbance

The aim is to understand the controls on species composition and structure of miombo woodlands subject to disturbances such as harvesting, cultivation and fire. This requires an understanding of the disturbance regimes generated by different biophysical and socioeconomic drivers, alone and interactively, and a focus on the regeneration and growth rates of key miombo woodland species, as well as on more basic physiology of miombo species. This experiment will work closely with other core experiments to assess the influence of human activity on ecosystem dynamics in contrast to the impacts of nutrients and climate.

Activity 1 Tree and Ecosystem Processes Across Moisture Gradients

The aim is to synthesize and extend the current fragmentary knowledge of the ecology and physiology of the dominant miombo trees to the point where it can be used in modelling. This activity will be based on analyses of existing forestry trials in the region, primarily by the scientists responsible for these trials, and will facilitate the synthesis, interpretation and extrapolation of these data and their incorporation into models. New measurements and studies are planned to fill gaps.

Task 1 Basic Measurements of Growth and Ecophysiology

Permanent sample plots will be established to monitor growth rates, litter fall, mortality and other basic parameters. Special field campaigns will measure gas exchange properties, light conditions, and other intensive measurements for use in development of process models. This task will build upon existing networks of sample plots, and will involve many regional institutions and scientists. An important analysis in future will involve quantifying the temporal and spatial patterns of various ecological indicators (growth rates, productivity, etc.), results of which will guide field methods in miombo ecosystems.

Task 2 Experiments on Effects of Fire and Herbivory on Tree Growth and Related Ecosystem Processes

There are several ongoing studies in the region on effects of controlled fire and herbivory on development of miombo stands. This task will continue these efforts and initiate new studies to provide adequate information for definition of response surfaces for model development. A priority will be the continuation of support for field studies that have been going on for many years but are in danger of abandonment due to funding constraints.

Task 3 Observations and Modelling of Phenology

High temporal resolution satellite data (AVHRR) provide a useful record of phenological changes in miombo systems. What is needed is a wide network of field observations of phenology across the extent of miombo woodlands to provide data to calibrate and validate the AVHRR products. Field observations are particularly important as leaf fall and leaf development is very variable in miombo species (see review in Frost 1996).

Activity 2 Development of Patch Dynamics Models

A patch dynamics model will be developed based on field measurements taken along gradients of moisture and intensities of land use. Permanent sample plots will be established (building upon existing studies where possible) and basic measurements will be taken and used to develop growth and dynamics models. Use of functional attributes instead of species will be explored as an alternative model of vegetation dynamics, to overcome data needs for all component species of the miombo. The patch model will be based on individual trees and will build upon past efforts in this area (Desanker and Prentice 1994, Desanker 1996). Emphasis will be on a model based on extensive field measurements, along the lines of the development of the SORTIE model (Pacala *et al.* 1996). Several hypotheses on the dynamics of savanna and miombo vegetation have been advanced in the past. These will be critically evaluated with any new data collected, as well as the bigger pool of data from studies from the many countries within the miombo network. In particular, the following hypotheses will be evaluated.

Hypothesis 1

There are multiple quasi-stable states in miombo vegetation structure and composition, the transitions among which are driven by the separate and combined impacts of land-use practices, wildlife (especially elephant) damage, fire, and, to a lesser extent, drought (Starfield *et al.* 1993).

Hypothesis 2

Closed-canopy miombo woodlands can degrade to open miombo woodland and secondary grasslands with repeated disturbances, but the process is reversible; that is, grasslands can revert to miombo (and, in the wetter regions, to semi-evergreen forest) when fire is excluded and other disturbances are minimized (Freson *et al.* 1974, Lawton 1978, Stromgaard 1988).

Reduced models using functional attribute approaches will be developed as well.

Task 1 Development of Patch-Scale Model of Vegetation Dynamics Based on Field Measurements

Task 2 Development of Miombo Dynamics Using Functional Attribute Approaches

Activity 3 Development of Ecosystem Process Models for Miombo

An ecosystem process model will be developed to study carbon, hydrological and nutrient dynamics of miombo ecosystems. There are several terrestrial ecosystem models that will be used as starting points, including the Global Biogeochemical Cycle (BGC) genre of models by Running and co-workers (*e.g.*, Running and Coughlan 1988, Running and Gower 1991, Milner, Running and Coble 1996), terrestrial biosphere model (HYBRID) (Friend *et al.* 1997), and the Terrestrial Ecosystem Model (TEM) (Melillo *et al.* 1993). Emphasis will be on defining a minimum model that can

be parameterized with current (or newly collected) data sets, one that will capture the main processes in miombo ecosystems. The Agricultural Catchments Research Unit (ACRU) hydrological model (Schulze 1995) will be used as the basis for the water cycle components. The new model for miombo will be used to analyse effects of land-cover changes on ecosystem processes, in particular, on carbon budgeting in miombo, and the nature and extent of influences of land use/land cover-changes on catchment hydrology.

Task 1 Development of a Terrestrial Ecosystem Model (TEM) of C, N, and P Pools and Fluxes for the Miombo Region

Task 2 Case Studies of Effects of Land-Use and Land-Cover Changes on Ecosystem Processes such as Catchment Hydrology and Carbon Budgets

Core Experiment 4: Nutrient Limitation in Miombo

The aim is to understand how nitrogen, phosphorus and water interact to control the primary production of miombo woodlands. These woodlands mostly occur on nutrient-poor, well drained, acid soils that have formed from long-term weathering of ancient erosional surfaces on the central plateau of Africa. Low leaf nitrogen contents and high potential for the soils to immobilize P suggest that miombo productivity is limited by N and P availability.

Losses of N through biogenic emissions, and N and P through pyrogenic emissions, may lower the stock of these nutrients unless balanced by wet and dry deposition and nitrogen-fixation. Heating of soil during slash fires can affect P transformations, making more P available to plants. Increases in pH due to the input of cations in ash can have a similar, though often transient, effect. These processes need to be studied and understood in the context of land use, associated disturbances of land cover, and the effects on fire regime. The key questions are:

- To what extent is primary production in miombo woodland controlled by levels of soil nitrogen, phosphorus, or both?
- What are the current patterns of N and P storage and availability in miombo soils and leaf tissues?
- How do miombo soils and plants respond to additions of N and P?
- Does increased N and P supply result in increased gaseous and leaching losses?
- Are losses of N and P in miombo in steady-state with reassimilation during the period between fires?

The working hypothesis is that both nitrogen and phosphorus control miombo productivity with N being most limiting in dry, sandy soils and P being most limiting in moist, clayey soils. This is because oxidic conditions in clay-rich soils reduce P availability, while the long-term effects of low N inputs, coupled with high biogenic emissions, reduce N availability in more sandy soils.

The research needed to test this hypothesis requires a combination of field surveys, field experiments, laboratory analyses and modelling. Field survey transects would allow the pattern of miombo N and P limitation to be demonstrated *a-priori*. Comparing the quantities of nutrients in leaf tissues collected across a range of miombo sites during the early growing season and at leaf abscission would provide a measure of internal recycling of nutrients; an index of nutrient availability; and an assessment of nutrient-use efficiency.

Activity 1 N and P in Miombo

The activity would be based on an incomplete N x P fertilization factorial experiment (possibly with additional micro-nutrient or complete nutrient treatments), aimed at showing the extent, if any, of N and P limitation, and of the interactions between the two. This experiment should be implemented at two or more sites, with block replication at each site. Treatment plots of 20 m x 20 m would ensure a sufficient area and number of trees on which to assess surface soil properties and plant responses. A minimum set of annual site measurements would include: soil N and P (total and available), leaf N and P, leaf litter fall estimation, leaf litter fall N and P, stem increment, soil microbial C, N and P and soil gaseous and leachate losses. The field experiments should last at least 5 years, preferably in conjunction with other miombo core research so that meteorological data and control sites can be shared. The experiments would be complemented by modelling.

Task 1 N x P Factorial Experiment

Task 2 Trace-Gas Fluxes from Miombo Landscapes

Task 3 Modelling of Nutrient Dynamics

Activity 2 Effects of Disturbance and Fire

Not all disturbances in miombo involve fire, nor is fire necessarily always a disturbance in the strict ecological sense. Nevertheless, the two are so often linked in miombo ecosystems that they are considered here jointly. The aim of this activity is to examine the linkages among land use, modifications and transformations of land cover, and changes in fire regime, and to investigate their impacts on soil properties, nutrient availability, and trace-gas fluxes. Other than fire, the main disturbances to be considered are partial and complete clearance of woodland, conversion of woodland to cropland, and heavy grazing (confined to drier areas).

Task 1 Effects of Fire on N and P Dynamics and on Trace-Gas Fluxes

Task 2 Impacts of Disturbance on N and P Dynamics and Trace-Gas Fluxes

Core Experiment 5: Biogeography and Distribution of Miombo

The quantitative environmental limits for miombo are not well known. Better knowledge of the environmental envelope would help predict shifts in distribution under an altered climate. It could also be used to develop a structural-functional classification of miombo and to enable more refined hypotheses about miombo functioning to be conceived. The current most commonly used classification scheme for miombo (White 1983) is based largely on floristics and so is unsuitable for predictive purposes. A new classification would need to take into account climate (moisture and temperature regimes); geomorphology (landform, relief, slope); vegetation (plant functional types, stand attributes); land use (semi-natural, coppice, cyclical clearance, permanent cultivation, grazed, degraded); and fire regime (frequency and timing of burning). An initial assessment of the utility of any functional classification would be to compare it with the results of existing static models of vegetation distribution, for example: biome models such as the Global Vegetation Distribution Model (DOLY) (Woodward and Smith 1994, Woodward *et al.* 1995) and the Global Vegetation Distribution Model (BIOME 3.0) (Hazeltine and Prentice 1996). Simulations of palaeoclimate and vegetation by 17 Climate Modelling Groups (PMIP) predict rather different outcomes in the nature and the magnitude of vegetation change, implying that miombo could be replaced either by montane forests or by xerophytic associations (Jolly *et al.* 1995), so there is some scope for improvement. The key questions:

- What determines the biophysical boundaries of modern miombo distribution?
- How has the distribution of miombo changed over the past 20K years?
- What can be inferred about past climates from these changes?
- What are the implications for predicting future changes using existing DGVMs?

Activity 1 Biophysical Definition of Miombo and Biogeographical Modelling

The aim is to develop the theoretical basis for developing and testing models of miombo distribution and its limits, and to generate appropriate databases. A major product will be a classification of miombo landscapes that can be used for prediction and extrapolation.

Task 1 Analyse Biophysical Limits and Develop a Classification System for Miombo

Task 2 Evaluate Global Vegetation Distribution Model Simulations in the Miombo Region

Activity 2 Palaeo Distribution of Miombo

The aim is to improve the understanding of the palaeoecology of the miombo region. The principal palaeoecological data consist of pollen data (fossil and modern), that can be collected in the 10-20 °S latitudinal zone, focused particularly on the Holocene period (10 kyr BP - modern) with a high resolution (~ 50 yr) pollen analysis. Fossil and modern pollen data would be incorporated in the IGBP Global Analysis and Integrative Modelling (GAIM) BIOME 6000 Global Biome database (modern, 6 and 18 kyr), and the African Pollen Database (closely connected with the European Pollen Database (EPD), North Americal Pollen Database (NAPD), and National Geophysical Data Center (NGDC) databases). A schema for the proposed palaeoecological studies in miombo is shown in Figure 4.

Task 1 **Identify Climatic and Human Forcing Factors on Distribution of Miombo**

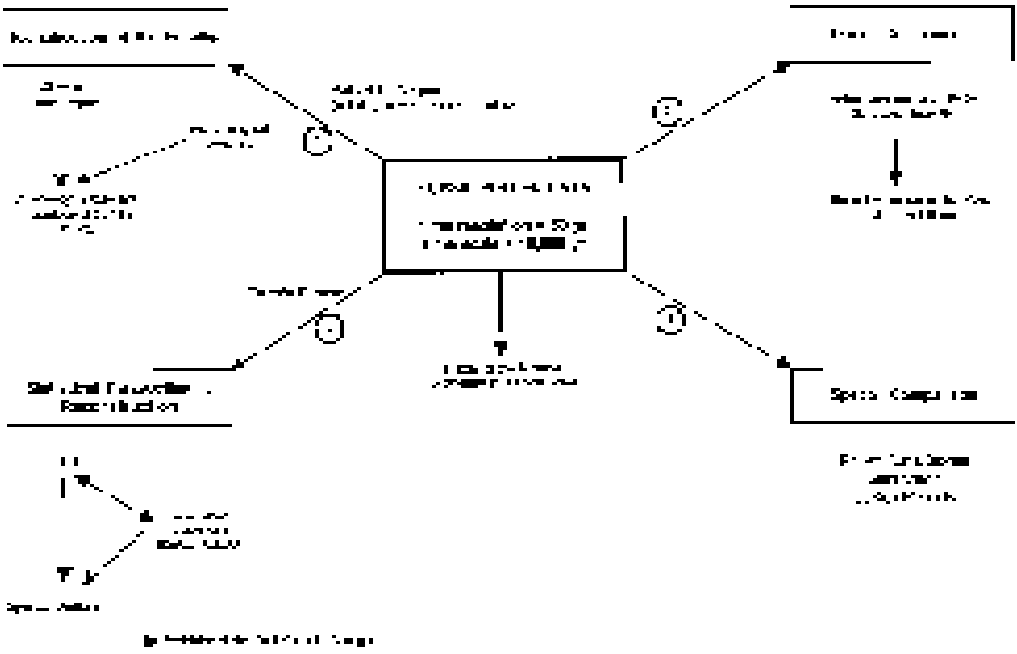
Task 2 **Reconstruct Palaeoclimate**

Task 3 **Compare Pollen Diagram with Simulated Biomass Using a Patch Dynamics Model**

Task 4 **Compare Spatial Pollen Reconstructions with Biome Simulations at Key Periods**

Figure 4

Flow chart of the proposed Palaeoecological Experiment on Miombo. The circled numbers correspond to Core Experiment 5, Activity 2, Tasks 1-4 in the text, T and P are temperature and precipitation.



Core Experiment 6: Regional Primary Production and Carbon Balance of Miombo

This research is designed to assess the impacts of changes in land cover at landscape and larger scales, and to test the validity of current models developed for other ecosystems to see if they can be used to represent vegetation-climate interactions in seasonally dry tropical ecosystems such as miombo. Primary production can be modelled with a reasonable degree of accuracy using models driven by climate, soil nutrient data and remotely sensed measurements of absorbed radiation. The primary production is then allocated to various constituents of the vegetation, determining wood, herbaceous, crop and other components of production. Each of these components provides different resources for people, livestock and wildlife. Such allocation models have been developed for a wide range of global vegetation types but have not yet been applied to miombo.

A range of models are also available that describe the transfer of water between the soil, vegetation, and atmosphere at a patch scale (so-called SVAT models). These can be linked to models of the movement of water through the soil at the landscape scale and, through them, to regional-scale climate models that represent the behaviour of the atmosphere over a mosaic of vegetation types. These models in turn are being integrated into general circulation models (GCMs) of climate processes that function at continental and global scales, with the result that the complete land surface-atmosphere system can be modelled for the first time. Initial experiments with such models indicate that land surface properties are much more important than is commonly appreciated. For instance, degradation of primary woodland to bare ground can reduce transpiration sufficiently to increase the probability of drought in adjacent regions. Increased atmospheric levels of CO_2 may cause stomatal closure, with similar consequences.

Integrated process-based models that combine the carbon, nutrient and hydrological cycles within an ecosystem can be used therefore to predict the consequences of changes in driving variables both on vegetation properties, such as composition, biomass and leaf area, and on regional hydrological and climate processes. A schema for such a model is shown in Figure 5.

A combined study involving experiments and modelling would provide the ideal opportunity to test the applicability of such models to tropical subhumid seasonal ecosystems such as miombo. Moreover, the integration of production and allocation models, scaled-up and validated at a landscape scale, would extend measurements of carbon assimilation and storage both spatially, from local research sites to the region, and in time. Accurately parameterizing and testing such models for miombo is the essential first step of the process. The key questions:

- How well do the existing land surface models predict the exchange of energy, water and gases between miombo landscapes and the atmosphere?
- How much change to miombo land cover can be tolerated before negative regional or global effects become apparent?

Activity 1 Regional Primary Production Modelling

Two modelling approaches will be used: those based on remote sensing, and those based on climatic and soil drivers. The models will be implemented at a minimum of atleast two study sites (wet and dry) miombo. The aim will be to predict regional primary production at 1 km^2 scale resolution.

Task 1 Parameterize and Validate Remote Sensing of NPP

Task 2 Development of a Model of Production and Biomass Allocation Among Different Plant Life-Forms at an Aggregated Scale (1 x 1 km)

Activity 2 Soil-Vegetation-Atmosphere Interactions Under Different Land-Uses

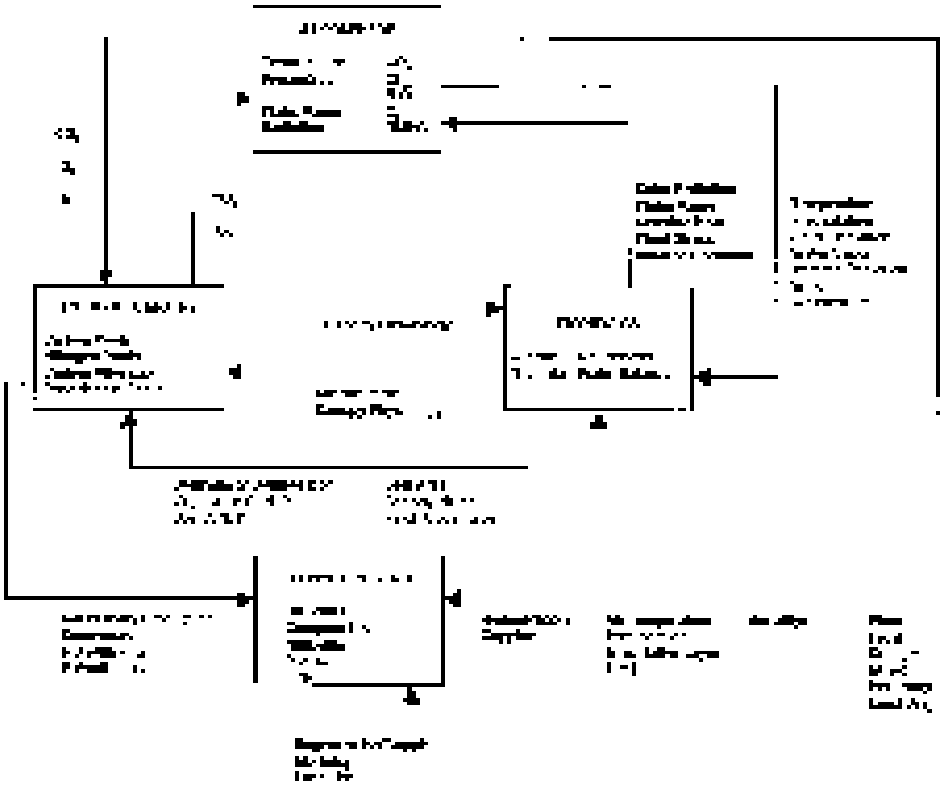
This activity requires that at least two sites be equipped with sophisticated boundary layer micrometeorology equipment, and that indices of net primary production (NPP) be collected by traditional mensural methods at several other sites. The initial aim of the activity is to acquire the knowledge needed to model regional fluxes of energy, water and trace gases using measurement of fluxes made at the patch scale, under different land uses and land cover types. The eventual aim is to assess the likely impact on regional climate of changes in land uses and land cover.

Task 1 SVAT Model Parameterization and Basic Measurements

Task 2 Simulation of Land-Use Effects on Regional Climate Through Linked SVAT Models and GCMs

Figure 5

Interactions between land surfaces and the atmosphere. Boxes denote the atmosphere and the three components of land-atmosphere interactions: biophysics, biogeochemistry, and ecosystem state. Text within boxes indicate important state variables. Arrows indicate variables exchanged between component models. Ecosystem state affects biogeochemistry and biophysics through community composition, leaf area index, canopy height, cover type, and carbon, phosphorus and nitrogen pools (modified from Bonan, 1995).



Core Experiment 7: Sustainable Natural Resource Management

A considerable amount of research is already being undertaken in the region on the economics of rural households; the use of land and natural products; the value of these products; indigenous technical knowledge, beliefs, and practices; and local-level management of natural resources (see Bradley and McNamara 1993, Dewees 1994, Carter and Murwira 1995, Hot Springs Working Group 1995, Campbell [in press]). Most of this research is participatory and development-orientated; almost all of it recognizes the depth of indigenous technical knowledge and beliefs about natural processes and their products. Much of this kind of research is central to the programmes of national and regional institutions.

The Miombo Network does not intend to duplicate, divert or compete with these initiatives in any way. Instead, Network activities aim to provide a forum in which the wider, global-change aspects of various land- and resource-use practices can be considered. The aim of this 'experiment' therefore is to link the outputs of the biophysical studies and socioeconomic research at household and community levels, the levels at which most operative decisions on land- and natural resource-use are being made. This linkage operates in both directions: household- and community-level decisions drive changes in land use and land cover; resource availability at the landscape level is one of the main determinants of such decisions. The goal is to understand sufficiently well the processes governing the demand for, and the supply and regenerative capacity of, miombo resources to be able to predict the limits of sustainable use for any given case.

Activity 1 Natural Resource Use at the Household Level

The aim of this activity is to quantify the extent of dependence of households on the miombo landscape, in terms of food, water, fuel, timber and other natural resources, and how that dependency changes where substitutable resources are available. Much work has already been done, and continues, on this issue in the region. Some of the work has been synthesized but more needs to be done to determine the nature and scope of any generalizations that can be made. The Miombo Network will seek to promote further synthesis to search for such generalizations; to identify the issues requiring more research; and to explore the integration of biophysical and socioeconomic research outputs.

Task 1 Synthesis of Existing Information on the Nature and Extent of, and Trends in, the Uses of Miombo Resources

Activity 2 Development of Rule-based Models for Natural Resource Management

The aim of this activity is examine ways in which knowledge gained by the Miombo Network can best be transferred to the management arena. Rule-based modelling may be a relatively transparent and robust way to do this. The key areas of concern for management in this regard are the system-wide consequences of changing land cover, associated with different land uses, and sustainable options for using miombo landscapes and resources. This activity will be undertaken in conjunction with Integrating Activity 3.

Task 1 Workshops to Design Models and Construct Rule Databases

Task 2 Validation of Models

Activity 3 Decision Support for Options to Reduce Trace-Gas Emissions and Minimize Forest-Cover Conversion

The aim of this activity is to support policy-making with respect to greenhouse gas mitigation. Although the countries of the miombo region are not presently required to reduce greenhouse gas emissions under the Framework Convention on Climate Change (since they are not Annex 1 countries), they will have to ultimately. They may wish to explore the possibilities of 'Actions Implemented Jointly' with Annex 1 countries before that time. This activity should facilitate that process.

Task 1 Develop Sector Models for Forestry, Agriculture and Community Land Use of Natural Resources

Task 2 Integrate Components into Decision Support System Models

Task 3 Test Decision Support Models in at Least Two Countries

Core Experiment 8: Integrating Activities

In addition to the previous outlined experiments and associated activities and tasks there are a number of integrating activities which combine the experimental products and results in synthetic analyses. The following activities will lead towards an integrated assessment for the region providing input for policy and management.

Activity 1 Development and Dissemination of Regional Databases

The aim is to provide scientists and decision-makers in the region and elsewhere with regional-scale data on physical features (topography, climate, soils, vegetation, geology, hydrology), biological characteristics (vegetation maps, NDVI statistics, livestock and wildlife numbers, animal diseases), and socio-economic attributes (demography, agricultural and economic indicators, land tenure regimes, land use and other measures of natural resource use) in an easily accessible format. There is a relative wealth of data available but much of it is fragmented, not easily accessible, in incompatible formats, and often only available outside the region or too expensive for individual scientists to afford. The main proposed medium for dissemination is CD-ROM, allowing large amounts of data to be stored relatively cheaply, and made accessible to those with a reasonable computer and a CD-ROM drive. The LUCC/DIS Miombo CD is a pilot project of this activity.

The production of a CD-ROM set will mean that all participants have access to standardized data, ensuring some consistency in the inputs to models and arguments, at least until it can be shown that the currently available data are inadequate. Access to, and discussion about, common data sets could also stimulate new questions, encourage collaboration, and enhance the rigor of analyses. Data quality is still uncertain and probably patchy. The compiled data sets, with appropriate caveats, could serve to test and, where necessary, refine both the data and the procedures by which they are collected.

Given the tight linkage between miombo ecology and human land-use, it is important that the Miombo Network undertake a fully integrated study. The incorporation of both physical and socio-economic data sets in the database would encourage Network scientists to think hard about: (i) the value of, and potential for, integration; (ii) the kinds of data required and their scales of resolution; and (iii) the problem of the often different scales at which biophysical and social scientists work, and experiments with integrated analyses across these scales.

Activity 2 Multi-Model Analysis of the Effects of Land Use and Land-Cover Changes

This activity is designed to link the various models developed at different spatial and temporal scales in the Miombo Network. The aim is to produce an integrated framework with which to assess the likely impacts of changes in land use and land cover on local and regional climate, natural resources, hydrological processes, and carbon and trace gas emissions. The types of models that will need to be linked in-

clude process based vegetation dynamics models; SVATs and NPP models; basin-wide hydrological models; models of trace gas emissions; macroeconomic diagnostic models; and household-level micro-economic models. (See Box 3 for a list of potential models, their capabilities, and examples drawn from existing models.)

Box 3

Summary of Potential Models and Modelling Activities.

Model Capability	Example(s)	Reference
Land Use and Land Cover	GEOMOD IMAGE 2.0 CLUE	Pontius 1995 Alcamo 1994 Veldkamp and Fresco 1996
Succession Models	MIOMBO ZELIG SORTIE FATE	Desanker and Prentice 1994 Smith and Urban 1988 Pacala *et al.* 1996 Noble and Slatyer 1980
Ecosystem Biogeochemistry	CENTURY TEM	Parton *et al.* 1993 Melillo *et al.* 1993
Ecosystem Production and Allocation	HYBRID TCX GLO-NEP BIOMASS	Friend, *et al.* 1997 Bonan 1995 Prince and Goward 1995 McMutrie *et al.* 1990
Water and Energy Exchange Across Land/Atmosphere Interface	SVATs (such as SiB and BATS) BIOME-BGC	Xue *et al.* 1991; Dickinson *et al.* 1992 Running and Hunt 1993
Dynamic Global Vegetation Distribution	DOLY PLAI BIOME 3.0	Woodward *et al.* 1995 Plöchl and Cramer 1995 Haxeltine and Prentice 1996
Fire Emissions Model	FIRE	Scholes *et al.* 1996b
Land Use and Catchment Hydrology	ACRU	Schulze 1995
Integrated Analysis	GRASSMAN MEXES	Howden *et al.* 1994 Fedra *et al.* 1987
Forest Sector Analysis and Econometric Modelling	IIASA	Sedjo and Lyon 1990
Socio-Economic Models	GXM	Meyer and Turner 1994; Liverman 1989

Activity 3 Analysis of Sustainable Management Options for Miombo

The aim of this activity is to analyse the models developed by the Miombo Network for outputs relevant to the issue of sustainable management of miombo. Those findings that are considered to be sufficiently robust will form inputs to Activity 2 of Core Experiment 7 where the actual rule-based management models will be developed. Figure 6 shows the flow of data, experiments and modelling activities from the various core experiments, culminating in an integrated analysis of sustainable management options for miombo.

Activity 4 Global Integration of Results with Other Dry Forest Transect Studies

The aim of this activity is to synthesize the findings of the Miombo Network with those of other, related, IGBP Transect studies, to enhance their value and generality. The Miombo Network bridges the humid tropical network studies (such as the Large-Scale Biosphere-Atmosphere study in the Amazon, and the Southeast Asia Network) and the subtropical savanna transects, such as the Kalahari Transect in southern Africa, Savannas in the Long Term (SALT) in West Africa, and the Northern Australia Tropical Transect (NATT). The synthesis will be achieved by holding joint workshops, sharing models, and possibly conducting joint experiments.

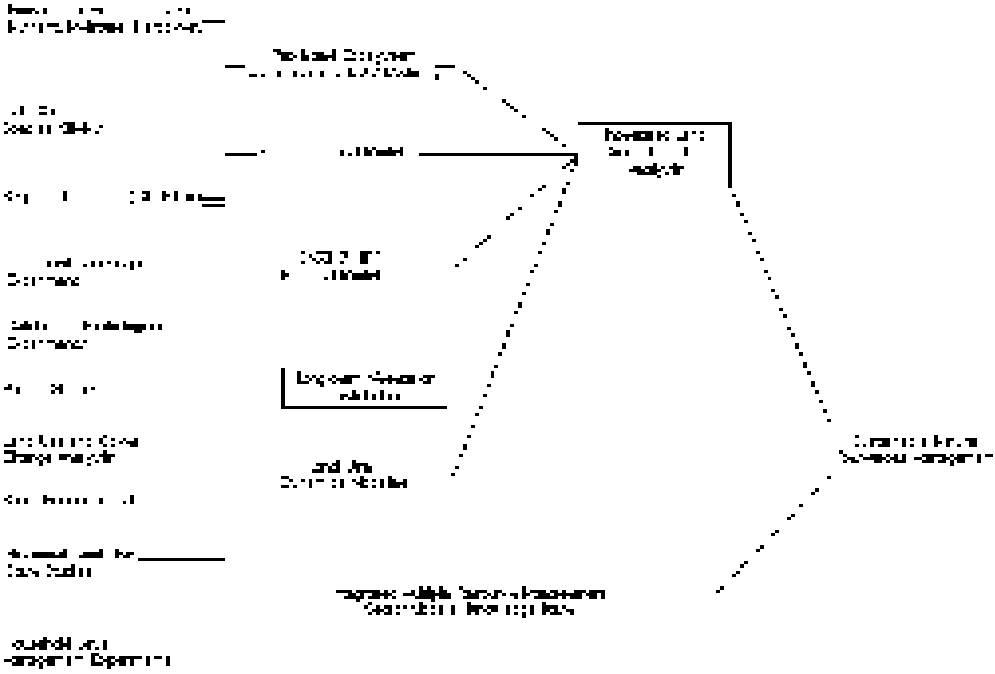
Activity 5 Individual and Institutional Capacity-Building

This activity aims to promote the transfer of technical skills and knowledge from international collaborators to the region and, equally importantly, to promote the recognition of regional scientists, with their knowledge and understanding of ecological and social processes in miombo, through encouraging their participation in global change research. The Network will work with START to support existing relevant initiatives being undertaken by mid-career regional scientists, as well to create new opportunities for early-career and post-graduate scientists from the region. In the case of scientists already working for national and regional institutions, the commitment to support their activities necessarily also implies support for their institutions, where appropriate.

Three complementary levels of involvement are anticipated: sharing information; sharing resources; and joint research. Sharing information will be promoted by making the CD-ROM data sets readily available; by exchanging ideas through workshops, e-mail and newsletters; and by providing opportunities to link with international networks operating at the cutting edge of scientific and social research. Sharing resources will involve assistance with obtaining funds for research; upgrading of study sites, including net transfers of equipment to the region; and developing opportunities for advanced study by regional graduates. Joint research will be achieved by developing collaborative projects involving individuals and groups with different and complementary skills. A major commitment on the part of the Miombo Network is obviously to obtain the resources needed to facilitate this activity.

Figure 6

Flow of data, experiments, modelling, and analysis.



Sites

The IGBP concept of a 'transect' involves linking sites which occupy different positions along some gradient relevant to global change, such as rainfall, temperature, or land-use. The idea is that when analysed together, the range of sites will provide more information about the response of ecosystems to changes in that major gradient, than if the sites were analysed alone. The sites need not fall along a geographical line; a network of sites would work just as well. The 'transect' is conceptual. The emphasis is on regional-scale impacts. The Miombo Network satisfies these conditions, and would fill a vital gap in the IGBP Transect portfolio by covering a gradient of land-use intensity in African subhumid seasonal woodlands.

Types of Sites

Study Sub-Regions

Study Sub-Regions will encompass a full range of the main miombo landscapes and land-cover types characterizing a region, as well as all major land-use practices. A Study Sub-Region (<200x200km) will contain at least one Study Site (10X10km) and should be reasonably accessible. Fine-scale spatial data sets on soils, vegetation types, land cover, land-cover change, and climate data will be required. They should extend across at least one Landsat scene. Comparable satellite imagery should be periodically available from 1972 to date.

Study Sites

These should be at least 10 x 10 km in extent, to permit the reliable use of remote sensing and micro-meteorological techniques, nested in Study Sub-Regions. The disturbance, nutrient and flux experiments will be conducted at these Study Sites. Key aspects of the carbon and nutrient pools and fluxes will be fully monitored and vegetation structure and dynamics described. The information to be collected will follow the Global Terrestrial Observing System (GTOS) hierarchical protocols (Heal *et al.* 1993).

Integrated Study Sites

Many categories of environmental and biological information are needed, both to understand the functioning of miombo and to parameterize climate models of the miombo region. Knowledge of the water, energy, nutrient and carbon balances, together with the responses of these to utilization, underpins the efforts to model climate, primary production and other aspects of miombo function. Certain types of measurements require expensive equipment that cannot reasonably be expected to be located at all Study Sites, hence we propose a specially category of instrumented study sites (Integrated Study Sites) at which the more specialized but critical measurements would be made. Equipment needed to make more difficult and demanding measurements, but which does not need to be used continuously at every site, could be provided in a mobile laboratory, together with the technical staff needed to operate the equipment, that would visit both Integrated Study Sites and subsidiary study sites. The integrated study sites utilized by the Miombo Network will provide good candidate locations for the collection of *in-situ* data as part of the International Global Observing Systems and in particular the Global Terrestrial Observing System (Heal *et al.* 1993).

The Integrated Study Sites will be fully instrumented for radiative transfer, water, energy and CO_2 flux measurements. At least two such sites are proposed, one each in wet and dry miombo, to explore the main axis of variation in climate. The sites should be located where there is a diversity of land uses and land cover. If possible, they should encompass a small catchment, and should include at least a 3 x 3 km area of non-manipulated vegetation, to allow monitoring using coarse resolution satellite remote sensing. The integrated sites should also be situated next to the disturbance and nutrient dynamics study sites, where vegetation structure and dynamics are described and the associated carbon and nutrient pools and fluxes measured. These sites will be overflown by flux-monitoring aircraft at critical times during the study to measure spatial variation of fluxes (including CO_2) at a larger scale.

Satellite Product Validation Test Sites

The generation of regional and global data sets from remotely sensed data is a high priority for the space agencies. These fields of geophysical parameters will provide an input to the modelling activities being undertaken as part of the Miombo Network experiments. Validation of these products to understand their accuracy and uncertainties is an important prerequisite to their use. Remote sensing scientists and regional scientists from the Miombo Network could obtain mutual benefit from validation at selected Miombo test sites. The launch of the NASA EOS Programme in 1998 offers an important opportunity for site characterization and data validation.

Site Selection

Two approaches could be adopted to site selection, top-down and bottom-up. While the first is theoretically more desirable, practicality and time dictate that the choice of sites will be based initially on existing sites. It will be important to assess the regional distribution of such sites and to fill gaps in coverage where necessary. The choice of Study Sites and Integrated Study Sites will be done early in the programme to permit establishment of long term measurements and in close consultation with regional and national institutions and their scientists, and is considered to be an important part of the process of establishing cooperative programmes.

Priorities and Scheduling

The research agenda laid out here is substantial and it clearly cannot be addressed all at once. Moreover, as the IGBP Miombo Network is to be founded on strong regional inputs and cooperation, it must start with initiatives to build on and support existing activities. New research will be implemented as opportunities, funds and personnel permit. Although individuals and institutions are normally expected to secure their own source of funding for global change research, in the case of regionally-based programmes such as the Miombo Network, local sources of funds for such research are either non-existent or severely limited. Most of these funds will have to be sought elsewhere. Collaboration between scientists from developed countries and those from the region will be essential to obtain the funds needed to initiate activities.

The priority is to secure the resources needed to launch the programme. Four key actions are highlighted in this regard:

- To seek support for those existing activities where a moderate input of funds or other resources would catalyze the production of data and analyses relevant to the overall aims of the Network (*e.g.,* tree growth and regeneration studies - Core Experiment 3, Activity 1)

- To develop proposals for those activities in which there is already an expressed interest in potentially funding research in the region (*e.g.,* the use of remote sensing to assess the nature and extent of land-use and land-cover change in the region - Core Experiments 1 and 2)

- To obtain funding for those activities that could produce results in a relatively short time, establishing a 'track record', which can be used in turn to leverage more substantial and longer-term support (*e.g.,* nature, extent and trends in natural resource use - Core Experiment 7, Activity 1; remote sensing of the timing, distribution and extent of fires - Core Experiment 2, Activity 2; historical land use patterns - Core Experiment 1, Activity 2)

- To initiate those activities which, because of their expense, complexity and time requirements, need extended lead times to secure the necessary funds, equipment and personnel (*e.g.,* broad-scale measurements of primary production and soil-vegetation-atmosphere interactions - Core Experiment 6).

A proposed schedule of data activities, experiments and modelling is shown in Figure 7. Capacity building and initial research proposals are being submitted through LUCC, START, and GCTE to funding agencies. START has provided several visiting fellowships to miombo scientists to assist with proposal development and to initiate training.

Figure 7

Proposed schedule of Miombo Network programmes.

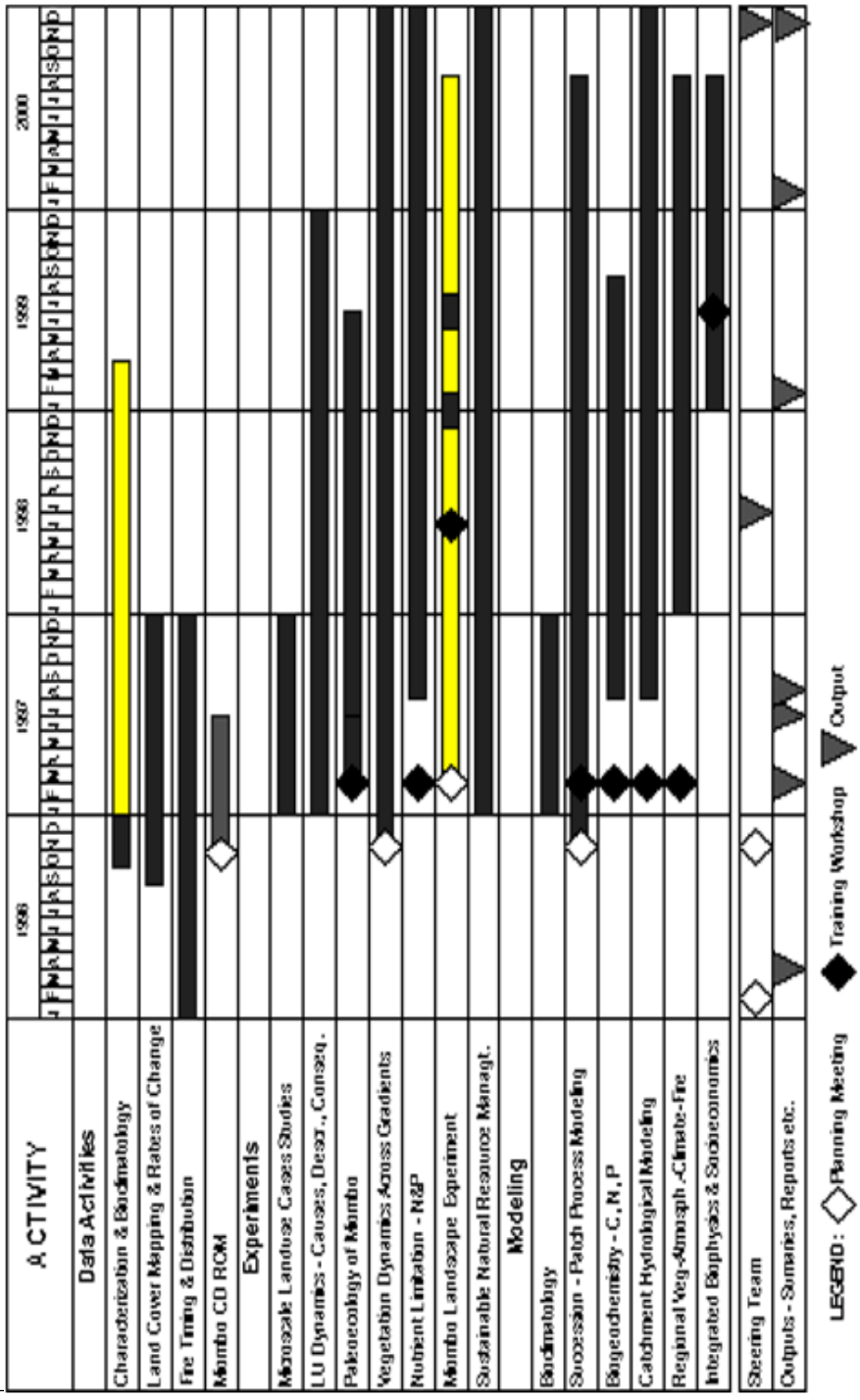
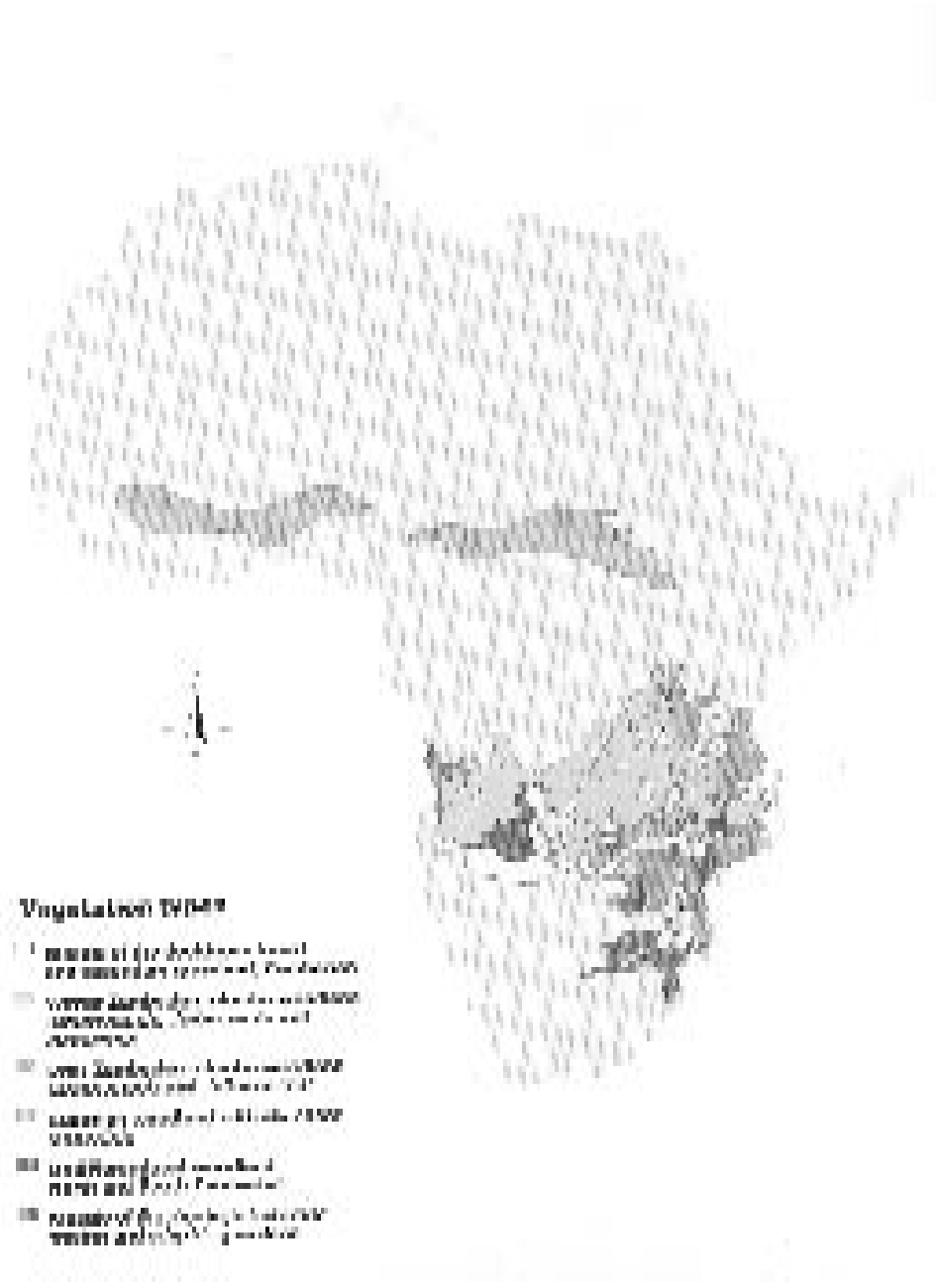


Figure 2

The distribution of miombo ecosystems as defined by this project. The total area is 2.8 million km^2.



“Kafue”

Miombo woodland on hills above the Kafue River gorge, Zambia (photo. P.G.H. Frost)

“Miombo Woodland”

Miombo woodland in the wet season has a relatively dense canopy that reduces the amount of light reaching the understorey, limiting herbaceous production in mature woodland stands. Lake Chivero, Harare (photo. P.G.H. Frost)

“Chipya”

Frequent, intense, late dry-season fires transform miombo woodlands over time to chipya, a wooded grassland with scattered fire-resistant trees. Kafue National Park, Zambia (photo. P.G.H. Frost)

"*Brachystegia Glaucescens*"

Brachystegia glaucescens is a fire-sensitive species, confined largely to hills and rocky outcrops where it is more protected from fire. Harare, Zimbabwe (photo. P.G.H. Frost)

"Charcoal Trade"

Bikers hauling charcoal from wooded areas into the City where whole bags are sold to street vendors to resell to the general public. Endless lines of bikers can be seen in main routes into the city daily. Larger loads are hauled by trucks. Chileka Road, Blantyre, Malawi (Photo. P. Desanker)

"Chitemene"

Slash-and-burn agriculture is widely practised in the wetter parts of the miombo region to open up and fertilise fields for the cultivation of rains, pulses, cassava and other root crops. Kaoma, Zambia (photo. P.G.H. Frost)

“Aerial”

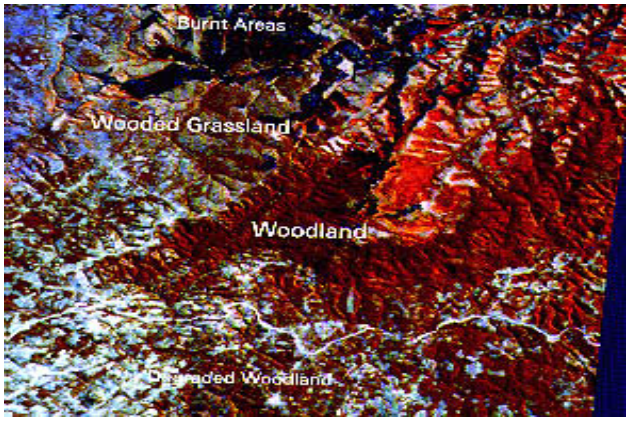
Aerial view of a relatively undisturbed dry miombo woodland, Marondera, Zimbabwe (photo. P.G.H. Frost)

“Flush”

The pattern of leaf flush in miombo differs from those of other deciduous tropical dry forests and woodlands. New leaves are produced up to two months before the start of the annual rains. The expanding leaves of some species, notably *Brachystegia spp.*, are saturated with anthocyanins, which may protect them from herbivores, pathogens, or UV radiation. Cristonbank, Zimbabwe (photo. P.G.H. Frost)

“TM”

A typical raw Landsat TM scene (bands 5,4,3) for Kasungu, Malawi. The deeper reds show increasing woodiness. (Image processing by M. Jaiteh)



Project Management and Institutions

The Miombo Network will be managed by a Network Coordinator (NC). The NC will function under the direction of a Joint Task Team (JTT) composed of representatives of regional participating institutions and individuals, and from the relevant IGBP Programme Elements (GCTE, IGAC, BAHC, LUCC with IHDP , and PAGES), Framework Activities (DIS, GAIM, and START). The function of the NC will be to facilitate the activities of the network by promoting communication; disseminating information about activities, meetings, research openings, and funding opportunities; assisting researchers prepare proposals for funding; and contributing to capacity building where possible. In the interests of effective integration, members of the TT should represent, where possible, a number of constituencies (for example, by being both regional researchers and representatives of IGBP Programme Elements). The main reporting link to the IGBP will be through the LUCC International Programme Office (IPO). START/SAFCOM will be responsible for initiating training activities and mobilizing of human resources within the region.

Data Management and Communication

At the Zomba meeting a breakout session was held to discuss data management and communication. The following section outlines the salient recommendations from that group. Further discussion will be needed to refine the data management aspects of the network.

The research undertaken within the network will be supported from a variety of sources, both national and international, and as such, individuals will need to follow the policies of their respective funding agencies with respect to third-party access to data. As part of the IGBP, however, the Miombo Network is committed to promoting a policy of data sharing among its members in accordance with the principles adopted by ICSU and IGBP and endorsed for the network at the Zomba workshop. In principle, data sets collected under the auspices of IGBP will be made available to the global change community within a reasonable time period. To have an effective network, it is important that participants in the network agree to a spirit of scientific collaboration and data and information exchange.

The primary data and results produced from research carried out within the Miombo Network will remain the property of the individual researcher or responsible institution. Existing data sets are treated likewise. Agreement must be reached beforehand on third-party access to, and use of, such data. Such agreements should preferably be in writing.

The Miombo Network is a cooperative initiative and so will aim to establish and maintain a network database of information about the study sites and associated ecological and socio-economic processes. The NC or some other person or institution approved by the JTT will be responsible for maintaining the database. Submission of data to the database will be voluntary, though strongly encouraged. Data submitted to the database will be evaluated before incorporation, to ensure consistency and quality. The voluntary submission of data to the database will be taken as a tacit agreement that the data can be made available for use by others, though a written agreement to this effect would be preferred. Nevertheless, full acknowledgement of the source of the data will be made. In some instances, co-authorship of a publication may be appropriate and will be encouraged. Where there is an interest or need to make a particular data set, not present in the database, more widely available

(*e.g.*, for modelling purposes), this will be negotiated in advance and the conditions for use established. In most cases, the person supplying the data should expect to be one of the authors on any publications resulting from the research.

Where there are separate activities at the same site requiring common data sets, a protocol for the collection of the data will be agreed among the researchers concerned. This protocol will specify the persons or group responsible, the methods to be used, details of the frequency and timing of data collection. Again, proper recognition will be given to individuals' contributions.

Information about ongoing and planned research activities will be circulated among network members by newsletter and e-mail. Where a planned or up-coming activity is likely to overlap with, contribute to, or need to depend on, an existing activity, the parties concerned will be notified and arrangements made to coordinate their efforts. This will be a primary responsibility of the NC. The NC will obviously need to be kept informed of planned, up-coming and on-going activities, and must establish effective lines of communication with Network researchers.

Finally, researchers from outside the region will need to obtain research clearance from the various national scientific research councils concerned, even for research carried out jointly with a national researcher. Responsibility for this rests with the individual researchers, though the means will be explored, through the offices of the national IGBP committees, where these exist, of facilitating this process. It is a normal requirement that, where appropriate, copies of all publications and reports arising from such research be deposited with the research council, the host institution, and the national archive. National IGBP committees in the region, as well as the relevant CPOs, will be kept informed of the research being carried out as part of the Miombo Network and will be asked to facilitate coordination.

Linkages

Relationship to National Needs and Priorities

National and regional natural resource managers are particularly interested in:

- Data on the actual and potential productivity of miombo ecosystems including data on non-wood forest products
- Information on the longer-term environmental and socioeconomic consequences of changes in both the intensity and kind of land use
- Country-wide data sets of land cover for analysis of food security, water and economic development
- Knowledge of miombo dynamics to assist in planning sustainable utilization and improvement of miombo
- Development of methods for integrating biophysical data with socioeconomic information in management and policy formulations
- Techniques that will facilitate the incorporation of scientific information into policy and management.

Information relevant to these topics should be generated by the proposed core experiments. The core experiments have been designed to ensure compatibility with ongoing research in miombo at national and regional levels. Where possible, and where invited, the proposed research will take place on study sites that are already part of national networks of sites. This should help catalyse and add value to these existing initiatives.

Core Experiment 7 on sustainable natural resource management is intended to be a major mechanism for integrating results of the various experiments with sustainable management of the miombo ecosystem by national institutions. Integrated models will be developed to provide an interface to the tools and methods developed in the miombo studies to policy makers and natural resources managers.

Linkages To IGBP Programmes

The following thematic areas of the main IGBP Programme Elements and Framework Activities are relevant to the Miombo Network. Coordination will be achieved by ensuring that each of the relevant core projects are represented on the Miombo JTT.

IGBP Programme Elements

Land-Use and Land Cover Change (LUCC)

- Human-induced changes in land cover over the last 300 years
- Major human causes of land-use change in different geographical and historical contexts
- Effects of changes in land use on land cover over the next 50 years
- Effects of current human and biophysical dynamics on the sustainability of specific types of land uses
- Potential effects of changes in climate and global biogeochemistry on both land use and land cover
- Integrated modelling and assessment of both regional and global models.

Biospheric Aspects of the Hydrological Cycle (BAHC)

- Biospheric processes associated with the hydrological cycle
- Riverine transport modelling
- Plant functional types with respect to water and energy exchange
- Hydrological pathways and quantities of element fluxes associated with land cover change.

Global Change and Terrestrial Ecosystems (GCTE)

- Biogeochemical cycles and vegetation dynamics
- Effects of global change on soil organic matter
- Sequestration and emissions of carbon from terrestrial ecosystems
- Landscape scale models of land cover and composition change

- Improved methods for predicting the distribution of terrestrial vegetation
- Development of dynamic vegetation models that can be linked to GCMs.

International Global Atmospheric Chemistry (IGAC)

- BIBEX: characterize production of gases and aerosols from biomass burning to determine the consequences of burning for regional and global atmospheric chemistry and climate
- BATGE: characterize the production and consumption of radiatively-active and ozone forming trace gases from soils and vegetation (primarily NO, N_2O and CH_4).

Land Ocean Interactions in the Coastal Zone (LOICZ)

- Determine the influence of land-use change, particularly the conversion from forest to agriculture, on the delivery of sediments and nutrients from land via river systems to coastal seas.

Past Global Changes (PAGES)

- Link with "BIOME 6000" (in collaboration with GAIM, DIS, GCTE), a global database of biomes based on macro-fossil evidence and fossil pollen data for key periods- 6 and 18 ka
- IDEAL and ALLDB (African Lake Level Database), as well as PAGES World Database (in Colorado).

IGBP Framework Activities

Data and Information Systems (DIS)

- Focus 1 - Data set production and validation
- Focus 2 - Data management aspects, data harmonization and standardization.

Global Analysis, Integration and Modelling (GAIM)

- Collaboration on modelling and synthesis.

System for Training and Research (START)

- Network building among collaborating partners
- Capacity building aspects.

The linkages between the IGBP Programme Elements and Framework Activities and IGBP/IHDP Land-Use and Land-Cover Change Core Project, and the Miombo Network, and their potential involvement in the core experiments, are summarized in Table 1.

Table 1

Linkages and involvement of Programme Elements/Research Programmes and Framework Activities in the Miombo Network.

MIOMBO EXPERIMENT	LUCC	GCTE	BAHC	PAGES	IGAC	GAIM	DIS	START (SAF)
1. Land Use Dynamics	X				X		X	X
2. Land Cover Dynamics	X	X			X		X	X
3. Ecosystem Dynamics & Disturbance	X	X	X			X		X
4. Nutrient Limitation in Miombo	X	X			X			X
5. Biogeography and Distribution of Miombo		X		X				X
6. Regional Primary Productivity and Carbon Balance	X	X	X			X		X
7. Sustainable Natural Resource Management	X	X						

External Linkages

As a regionally-based initiative, the Miombo Network will intersect a range of other national and regional programmes. These programmes have their own priorities and it is not the intention of the Network to attempt to supersede or divert their activities. But there are broader issues of global and regional environmental and socio-economic change that are not currently being addressed to the extent that they deserve. An understanding of the causes and consequences of these changes at national and regional levels is necessary if countries are to negotiate effectively in the framework of international conventions and agreements such as the Framework Convention on Climate Change and the Biodiversity Convention. The Miombo Network aims to catalyse and contribute to the development of that understanding in the region.

The operating principle of the Miombo Network is to collaborate with existing and proposed activities, to avoid duplication of effort, and to complement these activities both by facilitating existing research, where requested, and by promoting new research, where necessary, in order to understand the regional and global implications of land use and cover change in miombo. In collaborating with local and regional initiatives, the Miombo Network would bring data, models, techniques and insights obtained through its own and other IGBP/IHDP activities at larger scales that could enhance the value of national and regional initiatives.

The Miombo Network will also need to work closely with non-IGBP/IHDP activities. In particular it will need to take cognisance of related activities by the Center for International Forestry Research (CIFOR), the Alternatives to Slash-and-Burn (ASB) Project coordinated by the International Center for Research in Agroforestry (ICRAF), the International Livestock Research Institute (ILRI), and regional forestry research initiatives launched by the Southern African Development Community (SADC).

In particular, the Miombo Network will contribute to the SADC Forestry Sector project AAA 5.20, Sustainable Management of Indigenous Forests, with links to project AAA 5.23, Improvement and Strengthening of Forestry and Forest Products Research Institutions in the SADC Region, through activities 23.4 (Rehabilitation of Degraded Lands), 23.8 (Policy and Socio-Economic Studies Network) and 23.10 (Training in Research Methodologies).

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Acronyms and Abbreviations

ACRU	Agricultural Catchment Research Unit, Model
ALLDB	African Lake Level Data Base
ASB	Alternatives to Slash and Burn
AVHRR	Advanced Very High Resolution Radiometer
BAHC	Biospheric Aspects of the Hydrological Cycle (IGBP)
BGC	Global Biogeochemical Cycle Model
BIBEX	Biomass Burning Experiment (IGAC)
BIOME	Global Vegetation Distribution Model
CACGP	Commission on Atmospheric Chemistry and Global Pollution (IAMAS)
CCTA	Commission for Technical Cooperation in Africa South of the Sahara
CIESIN	Consortium for International Earth Science Information Network (USA)
CIFOR	Center for International Forestry Research
CNES	Centre National d´Etudes Spatiales (France)
CSA	Scientific Council for Africa South of the Sahara
DGVM	Dynamic Global Vegetation Model
DIS	Data and Information System (IGBP-DIS)
DMSP	Defence Mapping and Satellite Photographs
DOLY	Global Vegetation Distribution Model
EC	European Commission (European Union)
ECM	ectomycorrhizae
EOS	Earth Observing System (NASA)

EPD	European Pollen Database
FAO	Food and Agriculture Organization (UN)
GAIM	Global Analysis, Interpretation and Modelling (IGBP)
GCM	General Circulation Model
GCTE	Global Change and Terrestrial Ecosystems (IGBP)
GIMMS	Global Inventory, Monitoring and Modelling System (NASA)
GIS	Geographic Information System
GTOS	Global Terrestrial Observing System
HYBRID	Terrestrial Ecosystem Model
IAMAS	International Association of Meteorology and Atmospheric Science
ICRAF	International Center for Research on Agroforestry
ICSU	International Council of Scientific Unions
IGAC	International Global Atmospheric Chemistry Project (IGBP/ CACGP)
IGBP	International Geosphere-Biosphere Programme (ICSU)
IHDP	International Human Dimensions Programme on Global Environmental Change (ICSU/ISSC)
ILRI	International Livestock Research Institute
IPO	International Project Office (IGBP)
JTT	Joint Task Team
LANDSAT	Land Remote Sensing Satellite
LOICZ	Land-Ocean Interactions in the Coastal Zone
LUCC	Land-Use and Land-Cover Change (IGBP/IHDP)
MSS	Multispectral Scanner System
NASA	National Aeronautics and Space Administration (USA)
NAPD	North American Pollen Database
NATT	Northern Australian Tropical Transect
NC	Network Coordinator
NDVI	Normalized Difference Vegetation Index
NGDC	National Geophysical Data Center (NOAA, USA)
NOAA	National Oceanic and Atmospheric Administration
NPP	Net Primary Production
NTFP	non-timber forest products
PAGES	Past Global Changes (IGBP)

PMIP	Palaeoclimate Model Inter-comparison Project (PAGES)
REIMP	Resource Inventory Mapping Project (Zimbabwe)
SADC	Southern African Development Community
SAF	Southern Africa Region of START
SALT	Southern African Savannah in the Long Term
SC	Scientific Committee (IGBP)
SORTIE	Tree Model
SPOT	Système pour l´Observation de la Terre (France)
SSC	Scientific Steering Committee
START	Global Change System for Analysis, Research and Training (IGBP/IHDP/WCRP)
SVAT	Soil-Vegetation-Atmosphere Transfer
TEM	Terrestrial Ecosystem Model
TT	Task Team
UN	United Nations
VAM	vesicular-arbuscular mycorrhizae

Appendix I

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No. 12
The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP). The Initial Core Projects (1990). IGBP Secretariat, Stockholm, 330 pp.
The IGBP science plan is composed of research projects aimed at answering a number of key questions related to global change, through the establishment of Core Projects on the distinct sub-components of the Earth system, and related activities on data systems and research centres. An implementation strategy provides for its fulfilment.

No. 13
Terrestrial Biosphere Exchange with Global Atmospheric Chemistry. Terrestrial Biosphere Perspective of the IGAC Project: Companion to the Dookie Report. Report on the Recommendations from the SCOPE/IGBP Workshop on Trace-Gas Exchange in a Global Perspective. Sigtuna, Sweden, 19-23 February, 1990. Edited by P.A. Matson and D.S. Ojima (1990). IGBP Secretariat, Stockholm, 103 pp.
The Sigtuna workshop contributed to the development of a scientific action plan on terrestrial ecosystem gas exchange, complementing the International Global Atmospheric Chemistry Project (an IGBP Core Project) in areas of natural variability, boreal regions, global integration and modelling of fluxes, and trace gas fluxes in mid-latitude ecosystems.

No. 14

Coastal Ocean Fluxes and Resources. Report of a CP2 Ad Hoc Workshop, Tokyo, Japan, 19-22 September 1989. Edited by P. Holligan (1990). IGBP Secretariat, Stockholm, 53 pp.

The focus of IGBP Coordinating Panel 2 on Marine Biosphere-Atmosphere Interactions is the elucidation and prediction of the feedback loops between climate and ocean biogeochemistry under conditions of significant anthropogenic changes to the trace gas composition of the atmosphere. The workshop concentrated on global change and the coastal oceans.

No. 15

Global Change System for Analysis, Research and Training (START). Report of a Meeting at Bellagio, December 3-7, 1990. Edited by J.A. Eddy, T.F. Malone, J.J. McCarthy and T. Rosswall (1991). IGBP Secretariat, Stockholm, 40 pp. Also available in Spanish and French.

START is a plan for the development of an international network of regional research centres and sites to gather data and study global change problems in their regional contexts. These regions are identified. Issues to be addressed are: How changes in land use and industrial practices alter the water cycles, atmospheric chemistry and ecosystems dynamics; how regional changes affect global biogeochemical cycles and climate; and how global change leads to further regional change in the biospheric life support system.

No. 16

Report from the IGBP Regional Meeting for South America. São José dos Campos, SP, Brazil, 5-9 March 1990 (1991). IGBP Secretariat, Stockholm, 58 pp.

The workshop discussed, in a South American context, past global changes, the effects of climate change on terrestrial ecosystems, the role of ocean processes in global change, land transformation and global change processes, the importance of the Andes for general circulation models, and regional research centres. Recommendations promote the role of South American science in global change research.

No. 17

Plant-Water Interactions in Large-Scale Hydrological Modelling. Report of a Workshop, Vadstena, Sweden, 5-8 June 1990 (1991). IGBP Secretariat, Stockholm, 44 pp.

The workshop addressed plant-water interrelationships at landscape to continental scales: the spatial pattern at landscape level of the dynamics of water flows and waterborne fluxes of dissolved and suspended mater; plant/vegetation characteristics and properties affecting return flow to the atmosphere; methodological issues of large-scale modelling; research in humid tropical, semi-arid and temperate zones.

No. 18:1

The Recommendations of the Asian Workshop, New Delhi, India, February 11-15, 1991. Edited by R.R. Daniel (1991). IGBP Secretariat, Stockholm, 36 pp.

Recommendations of the Workshop address issues of prime concern to Asian countries, with reports and recommendations from Working Groups on IGBP Core Projects and key activities.

No. 18:2

Proceedings of the Asian Workshop, New Delhi, India, 11-15 February 1991. Edited by R.R. Daniel and B. Babuji. Madras, Committee on Science and Technology in Developing Countries (COSTED) and the Indian National Committee for the IGBP (1992). Madras, COSTED, Asia Regional Office, 152 pp.

The Proceedings include 19 papers on Earth system research and global environmental change in Asia, and national reports on global change programmes.

No. 19*

PAGES Past Global Changes Project: Proposed Implementation Plans for Research Activities. Edited by J.A. Eddy (1992). IGBP Secretariat, Stockholm, 112 pp.

The Past Global Changes (PAGES) project will secure better understanding of the natural and human-induced variations of the Earth system in the past, through studies of both natural and written records. Focus is on changes within two temporal streams: global changes for the period 2000 BP, and changes through a full glacial cycle. Implementation plans address: solar and orbital forcing and response, Earth system processes, rapid and abrupt global changes, multi-proxy mapping, palaeoclimatic and palaeoenvironmental modelling, advances in technology, management of palaeodata, and improved chronologies for palaeoenvironmental research.

No. 20*

Improved Global Data for Land Applications: A Proposal for a New High Resolution Data Set, Report of the Land Cover Working Group of IGBP-DIS. Edited by J.R. Townshend (1992). IGBP Secretariat, Stockholm, 75 pp.

This report outlines a proposal to produce a global data set at a spatial resolution of 1 km derived from the Advanced Very High Resolution Radiometer primarily for land applications. It defines the characteristics of the data set to meet a number of requirements of IGBP's science plan and outlines how it could be created. It presents the scientific requirements for a 1 km data set, the types and uses of AVHRR data, characteristics of a global 1 km data set, procedures, availability of current AVHRR 1 km data, and the management needs.

No. 21*

Global Change and Terrestrial Ecosystems: The Operational Plan. Edited by W.L. Steffen, B.H. Walker, J.I. Ingram and G.W. Koch (1992). IGBP Secretariat, Stockholm, 97 pp.

The objectives of GCTE are: to predict the effects of changes in climate, atmospheric composition, and land use on terrestrial ecosystems, including agricultural and production forest systems, and to determine how these effects lead to feedbacks to the atmosphere and the physical climate system. The research plan is divided into four foci: ecosystem physiology, change in ecosystem structure, global change impact on agriculture and forestry, and global change and ecological complexity. Research strategies are presented.

No. 22
Report from the START Regional Meeting for Southeast Asia. Arranged by the International Geosphere-Biosphere Programme: A Study of Global Change (IGBP), in collaboration with Human Dimensions of Global Environmental Change (HDGEC) Programme (1992). IGBP Secretariat, Stockholm, 114 pp.
The report presents general recommendations on global change research in the region, thematic studies relating to IGBP Core Project science programmes, global change research in studies of eight countries in the area, and conclusions from working groups on the participation of the region in research under the five established IGBP Core Projects and the related HDGEC programme.

No. 23
Joint Global Ocean Flux Study: Implementation Plan. Jointly published with the Scientific Committee on Oceanic Research (SCOR) (1992). IGBP Secretariat, Stockholm, 78 pp. (JGOFS Report No. 9)
The Report describes how the aims of JGOFS are being, and will be, achieved through global synthesis, large scale surveys, process studies, time series studies, investigations of the sedimentary record and continental margin boundary fluxes, and the JGOFS data management system.

No. 24
Relating Land use and Global Land-Cover Change: A Proposal for an IGBP-HDP Core Project. A report from the IGBP/HDP Working Group on Land-Use/Land-Cover Change. Edited by B. L. Turner, R. H. Moss, and D. L. Skole (1993. IGBP Secretariat, Stockholm, 65 pp. (Human Dimensions of Global Environmental Change Programme, HDP Report No. 5)
The report presents the main findings of the joint Working Group of the IGBP and the International Social Science Council on Land-Use/Land-Cover Change; it describes the research questions defined by the group and identifies the next steps needed to address the human causes of global land-cover change and to understand its overall importance. It calls for the development of a system to classify land-cover changes according to the socioeconomic driving forces. The knowledge gained will be used to develop a global land-use and land-cover change model that can be linked to other global environmental models.

No. 25
Land-Ocean Interactions in the Coastal Zone (LOICZ) Science Plan. Edited by P.M. Holligan and H. de Boois, with the assistance of members of the LOICZ Core Project Planning Committee (1993). IGBP Secretariat, Stockholm, 50 pp.
The report describes the new IGBP Core Project, giving the scientific background and objectives, and the four research foci. These are: the effects of global change (land and freshwater use, climate) on fluxes of materials in the coastal zone; coastal biogeomorphology and sea-level rise; carbon fluxes and trace gas emissions on the coastal zone; economic and social impacts of global change on coastal systems. The LOICZ project framework includes data synthesis and modelling, and implementation plans cover research priorities and the establishment of a Core Project office in the Netherlands.

No. 26

Towards a Global Terrestrial Observing System (GTOS): Detecting and Monitoring Change in Terrestrial Ecosystems. Report of the Fontainebleau Workshop. Edited by O. W. Heal, J.-C. Menaut and W. L. Steffen (1993). Paris: MAB, 71 pp. (UNESCO Man and the Biosphere Digest 14)

The Fontainebleau Workshop, July 1992, defined a strategy to initiate a global terrestrial monitoring system for the IGBP project on Global Change and Terrestrial Ecosystems, the French Observatory for the Sahara and the Sahel, and the UNESCO Man and the Biosphere programme, in combination with other existing and planned monitoring programmes. The report reviews existing organisations and networks, and drafts an operational plan.

No. 27*

Biospheric Aspects of the Hydrological Cycle. The Operational Plan. 1993. Edited by BAHC Core Project Office, Berlin (1993). IGBP Secretariat, Stockholm, 103 pp.

A presentation of the mandate, scope, principal subjects and structure of the BAHC research plan is followed by a full description of the four BAHC Foci: 1) Development, testing and validation of 1-dimensional soil-vegetation-atmosphere transfer (SVAT) models; 2) Regional-scale studies of land-surface properties and fluxes; 3) Diversity of biosphere-hydrosphere interactions; 4) The Weather Generator Project.

No. 28*

The IGBP in Action: The Work Plan 1994-1998. 1994. IGBP Secretariat, Stockholm, 151 pp.

This Report provides an overview of the global change research to be carried out under the aegis of the International Geosphere-Biosphere Programme over the next five years. It represents a follow-up to IGBP Report No. 12 (1990) that described the basic structure of the global change research programme, the scientific rationale for its component Core Projects and proposals for their development. The IGBP Core Projects and Framework Activities present their aims and work programme in an up-to-date synthesis of their science, operational and implementation plans.

No. 29

Africa and Global Change. A Report from a Meeting at Niamey, Niger, 23-27 November, 1992. (1994). IGBP Secretariat, Stockholm. (English and French under the same cover)55 pp.

A summary is given of the conference arranged by the Global Change System for Analysis, Research and Training (START) on behalf of the IGBP, the Human Dimensions of Global Environmental Change Programme (HDP), and the Joint Research Centre of the Commission of the European Communities (CEC) that describe the global change scientific research situation in Africa today.

No. 30

IGBP Global Modelling and Data Activities, 1994-1998. 1994. Strategy and Implementation Plans for Global Analysis, Interpretation and Modelling (GAIM) and the IGBP Data and Information System (IGBP-DIS). IGBP Secretariat, Stockholm, 86 pp.
This report sets out the goals and directions for GAIM and IGBP-DIS over the next five years, expanding on the recent overview of their activities within IGBP Report 28 (1994). It describes the work within IGBP-DIS directed at the assembly of global databases of land surface characteristics, and within GAIM, directed at modelling the global carbon cycle and climate-vegetation interaction.

No. 31

African Savannas and the Global Atmosphere. Research Agenda. 1994. Report of a joint IGBP/START/IGAC/GCTE/GAIM/DIS Workshop on African Savannas, Land use and Global Change: Interactions of Climate, Productivity and Emissions, 1-5 June 1993, Victoria Falls, Zimbabwe. Edited by C. Justice, B. Scholes and P. Frost. IGBP Secretariat, Stockholm, 53 pp.
The workshop focused on interactions between African savannas and the global atmosphere, specifically addressing land-atmosphere interactions, with emphasis on sources and sinks of trace gases and aerosol particles. The report discusses the ecology of African savannas, the research issues related to carbon sequestration, ongoing and proposed activities, and gives a research agenda.

No. 32

International Global Atmospheric Chemistry (IGAC) Project. The Operational Plan. 1994. IGBP Secretariat, Stockholm, 134 pp.
The goals of IGAC are to: develop a fundamental understanding of the processes that determine atmospheric composition; understand the interactions between atmospheric chemical composition and biospheric and climatic processes, and predict the impact of natural and anthropogenic forcings on the chemical composition of the atmosphere. The Operational Plan outlines the organisation of the project. The plan describes the seven Foci, their related Activities and Tasks, including for each the scientific rationale, the goals, strategies.

No. 33

Land-Ocean Interactions in the Coastal Zone. Implementation Plan. 1995. Edited by J.C. Pernetta and J.D. Milliman. IGBP Secretariat, Stockholm, 215 pp.
LOICZ is that component of the IGBP which focuses on the area of the Earth's surface where land, ocean and atmosphere meet and interact. The implementation plan describes the research , its activities and tasks, and the management and implementation requirements to achieve LOICZ 's science goals. These are, to determine at regional and global scales: the nature of these dynamic interactions, how changes in various compartments of the Earth system are affecting coastal zones and altering their role in global cycles, to assess how future changes in these areas will affect their use by people, and to provide a sound scientific basis for future integrated management of coastal areas on a sustainable basis.

No. 34

BAHC-IGAC-GCTE Science Task Team. Report of First Meeting. Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, 10-12 January, 1994. 1995. IGBP Secretariat, Stockholm, 45 pp.

The Science Task Team discussed and developed recommendations for multi-Core Project collaboration within the IGBP under three headings: process studies in terrestrial environments, integrated modelling efforts, and partnership with developing country scientists. Three interrelated themes considered under process studies are: transects and large-scale land surface experiments, fire, and wetlands. Methods for implementation and projects are identified.

No. 35

Land-Use and Land-Cover Change. Science/Research Plan. 1995. Edited by B. L. Turner II, D. Skole, S. Sanderson, G. Fischer, L. Fresco and R. Leemans. IGBP Secretariat, Stockholm, HDP Secretariat, Geneva, (IGBP Report 35/HDP Report 7) 132 pp.

The Science/Research Plan presents land-use and land-cover change and ties it to the overarching themes of global change. It briefly outlines what is currently known and what knowledge will be necessary to address the problem in the context of the broad agendas of IGBP and HDP. The three foci address by the plan are: (i) land-use dynamics, land-cover dynamics - comparative case study analysis, (ii) land-cover dynamics - direct observation and diagnostic models, and (iii) regional and global models - framework for integrative assessments.

No. 36

The IGBP Terrestrial Transects: Science Plan. 1995. Edited by G.W. Koch, R.J. Scholes, W.L. Steffen, P.M. Vitousek and B.H. Walker. IGBP Secretariat, Stockholm, 53. pp. Also available in Chinese.

The IGBP Terrestrial Transects are a set of integrated global change studies consisting of distributed observational studies and manipulative experiments coupled with modelling and synthesis activities. The transects are organised geographically, along existing gradients of underlying global change parameters, such as temperature, precipitation, and land use. The initial transects are located in four key regions, where the proposed transects contribute to the global change studies planned in each region.

No. 37

IGBP Northern Eurasia Study: Prospectus for an Integrated Global Change Research Project. 1996. Edited by W.L. Steffen and A.Z. Shvidenko. IGBP Secretariat, Stockholm, 95 pp. Also available in Russian.

This report was prepared by scientists representing BAHC, IGAC, and GCTE. It is a prospectus for an integrated hydrological, atmospheric chemical, biogeochemical and ecological global change study in the tundra/boreal region of Northern Eurasia. The unifying theme of the IGBP Northern Eurasia Study is the terrestrial carbon cycle and its controlling factors. Its most important overall objective is to determine how these will alter under the rapidly changing environmental conditions.

No. 38

Natural Disturbances and Human Land Use in Dynamic Global Vegetation Models. A report of a workshop co-convened by the GAIM, GCTE, LUCC, and IGBP-DIS Programme Elements of the IGBP. 1997. Edited by F.I. Woodward and W.L. Steffen. IGBP Secretariat, Stockholm, 49 pp.

This report summarises the findings and recommendations of an International Geosphere-Biosphere Programme (IGBP) Workshop which aimed to develop an approach to modelling landscape-scale disturbances in the context of global vegetation change.

No. 39

Modelling the Transport and Transformation of Terrestrial Materials to Freshwater and Coastal Ecosystems. A workshop report and recommendations for IGBP Inter-Programme Element Collaboration. 1997. Edited by C.J. Vörosmarty, R. Wasson and J. Richey. IGBP Secretariat, Stockholm, 84 pp.

This report is the major product of a three-day workshop entitled: "Modelling the Delivery of Terrestrial Materials to Freshwater and Coastal Ecosystems" held in Durham, NH, USA from 5-7 December 1994.

No. 40

Global Ocean Ecosystem Dynamics. Science Plan. 1997. Final editing by: R. Harris and the members of the GLOBEC Scientific Steering Committee (SSC). IGBP Secretariat, Stockholm, 83 pp.

Based on a draft plan written by the SCOR/IOC SSC for GLOBEC in 1994. That plan was itself based on a number of scientific reports generated by GLOBEC working groups and on discussions at the GLOBEC Strategic Planning Conference (Paris, July 1994). This document was presented to the Executive Committee of the Scientific Committee on Ocean Research (SC-SCOR) for approval (Cape Town, November 14-16 1995), and was approved by the SC-IGBP at their meeting in Beijing in October 1995. The members of the SCOR/IGBP CPPC were: B.J. Rothschild (Chair), R. Muench (Chief Editor), J. Field, B. Moore, J. Steele, J.-O. Strömberg, and T. Sugimoto.

No. 41

The Miombo Network: Framework for a Terrestrial Transect Study of Land-Use and Land-Cover Change in the Miombo Ecosystems of Central Africa. Conclusions of a meeting of the Miombo Network Workshop held in Zomba, Malawi, December 1995. Edited by P.V. Desanker, P.G.H. Frost, C.O. Justice, and R.J. Scholes. 1997. IGBP Secretariat, Stockholm, 109 pp.

This report describes the strategy for the Miombo Network Initiative, developed at an IGBP intercore-project workshop in Malawi in December 1995 and further refined during the Land Use and Cover Change (LUCC) Open Science Meeting in January 1996 and through consultation and review by the LUCC Scientific Steering Committee (SSC).

Book of Abstracts

Book of Abstracts. Natural and Anthropogenic Changes: Impacts on Global Biogeochemical Cycles. Asian Change in the Context of Global Change. Beijing, 23-25 October, 1995. IGBP Secretariat, Stockholm, 107 pp

This book of abstracts is a result of materials presented at the scientific symposium held in conjunction with the Fourth Scientific Advisory Council for the IGBP (SAC) held in Beijing, 23-25 October, 1995.

IGBP Booklet*

A Study of Global Change. 1989. Edited by IGBP Secretariat, Stockholm, 9pp.

Global Change: Reducing Uncertainties

Prepared by P. Williamson, with editorial assistance from the Scientific Committee for the IGBP (June, 1992; reprint August 1993), IGBP Secretariat, Stockholm, 40 pp.

IGBP Directory

IGBP Directory. No. 1, February 1994
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