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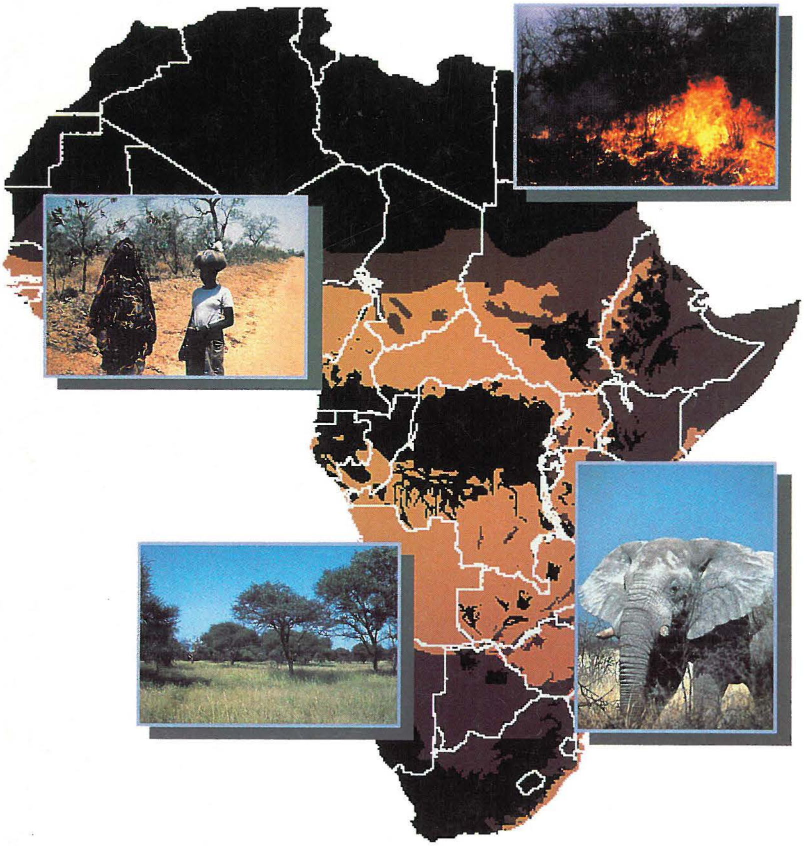

African Savannas and the Global Atmosphere

Research Agenda

The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP)
of the International Council of Scientific Unions (ICSU)
Stockholm, 1994

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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

2-5 June 1993

Victoria Falls, Zimbabwe

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Summary

The workshop was convened to bring together scientists involved in studying various aspects of the savannas of Africa, to discuss mutual research interests and to start to outline a regional research agenda to meet the common needs of the International Geosphere-Biosphere Programme (IGBP) Core Projects and regional scientists. The workshop focused on land-atmosphere interactions, with particular emphasis on sources and sinks of trace gases and aerosol particles.

Interest in African emissions has been boosted by the recent discovery of a seasonal maximum of tropospheric ozone over the southern tropical Atlantic. This anomaly has been linked to trace gas emissions in southern Africa resulting in the production and transport of O_3 and OH. The emissions are associated with the land use practices in African savannas. Biogenic (ruminants, soils and termites), pyrogenic (vegetation fires, domestic fuel wood burning and charcoal production) and industrial emissions are all potentially significant sources. Preliminary estimates suggest that biogenic and pyrogenic sources located in African savannas dominate the emissions.

The development of a dynamic model of emissions which is responsive to interannual variability as well as long term changes in climate and land use is an important interdisciplinary goal for the research community. Components of such a model would have to include estimation of fuel loads, emission factors and combustion completeness, soil emissions and herbivory. A fundamental requirement is the generation of a series of models of savanna ecosystem function.

The meeting was unanimous on the need for a regional effort to compile the existing data pertinent to the above research. Relevant data are currently scattered throughout the region in the grey literature and in national holdings. There is a scarcity of data related to trace gas emissions from the African savannas, although international initiatives such as the Dynamique et Chimie Atmospherique en Forêt Equatoriale (DECAFE) and the Southern African Fire Atmosphere Research Initiative (SAFARI) field programmes have provided new and interesting information. Quantification of the distribution and timing of fires is now possible through the use of daily coarse resolution satellite data. Similarly, our limited knowledge of the distribution and rates of land use change in Africa may be augmented using the twenty-year record of high resolution satellite data. The human dimensions to the research questions were identified, along with the difficulties in locating and compiling up-to-date data on human and animal populations, fuel wood consumption and charcoal production.

The meeting promoted dialogue between the atmospheric, ecological and social science communities, between field experimentalists and modellers, and between researchers from different geographical areas. It highlighted the commonalty of interest amongst several Core Projects and Framework Activities of the IGBP and identified areas that would benefit from joint activities. It exposed individual research efforts related to African emissions to a broader community and outlined a programme of research to reduce the current uncertainties. A number of new experiments were proposed and ways

to strengthen planned experiments were discussed. The meeting laid the foundation for a regional research programme. The urgent need for such a programme was discussed in the context of the requirements of the Intergovernmental Panel for Climate Change (IPCC) to develop national-level assessments of greenhouse gas emissions.

The meeting demonstrated that there is a community of researchers in Africa who are interested in participating in an interdisciplinary research programme associated with regional emissions estimation and modelling. The advantages of an African research initiative were apparent from the meeting, as was the need for the increased involvement of regional scientists at all levels within such a programme. The difficulties in supporting interdisciplinary, regional-scale studies through either national or international funding was recognised. Nevertheless, the regional nature of the research questions, the requirement for regionally applicable methodologies and the limited human resources to conduct the research are strong arguments for a coordinated regional approach. It is hoped that the System for Analysis, Research and Training (START) programme for Africa will include the proposed activities within the region as part of its regional research agendas.

Objectives

Several factors have combined over the past few years to focus more of the attention of the global change community on Africa:

- Preliminary measurements and calculations show that Africa is a significant source of gases and particles that influence the global radiation balance and which participate in the global ozone cycle
- Human population density, distribution and land uses are changing rapidly and substantially
- The START initiative, aimed at extending participation in three international programs (HDP/IGBP/WCRP) to all parts of the world, has launched activities in Africa.

The overall purpose of the workshop was to define research issues and areas of common interest between African and non-African scientists. The field of ecosystem-atmosphere interactions has the potential to be an area of shared interest, since it links issues of global concern to topics on which researchers from Africa have a history of expertise: fire, herbivory and land-use. Emissions of trace gases are a unifying theme between soil, vegetation, animals and atmosphere. In addition, many African countries are signatories to the Framework Convention on Climate Change, and therefore need to develop the capacity to conduct country studies on sources and sinks of anthropogenic greenhouse gases.

The objectives of the meeting were to:

- Review the processes of interaction between savannas and the global atmosphere, and place them in the context of the ecology of African savannas
- Determine the state of knowledge on production and consumption of gases from terrestrial ecosystems in Africa, identifying key processes, controls, points of management intervention and national policy implications
- Design a collaborative research strategy and programme to address the key uncertainties with respect to the impact of African savannas on the global atmosphere
- Design and coordinate an information system for gas emissions from Africa, and to provide an improved method of estimating national emissions for the 1995 IPCC assessment.

African Savannas and the Global Atmosphere

When plant biomass is burned CO_2 is released into the atmosphere, along with CO, CH_4, NO, N_2O, soot particles and a wide range of organic compounds, collectively called Non-Methane Hydrocarbons (NMHC) or Volatile Organic Carbon (VOC). These emissions alter the radiation budget of the Earth, either contributing to global warming (CO_2, CH_4 and N_2O) or in the case of the particles, helping to reduce it. Many of the compounds participate in the O_3 and OH cycles contributing to the production of tropospheric ozone (CH_4, NMHC, NO, CO). The nitrogen and sulphur compounds contribute to acid deposition, even in the absence of industrial emissions.

African savannas have burned naturally and under human influence for thousands of years. The CO_2 released by fires and decomposition must therefore be balanced by photosynthetic carbon assimilation in the long term, although recent changes in land use practices may have resulted in savannas becoming net sources or sinks of carbon. It is known that a significant portion of the total global biomass burning takes place in savannas, and that most of these savannas occur in Africa. Fire is an important factor in savanna ecology. In most savannas, fire is one of the four major determinants of vegetation structure, ecosystem function and biodiversity, along with climate, soils and herbivory. Burning of the dead, unpalatable grass in the dry season is an essential part of pastoral and hunter-gatherer systems in savannas. Fire is a valuable tool for bush control in savanna rangelands.

Except for CO_2, the trace gases emitted by fires constitute a net flux into the atmosphere, since they are not absorbed by subsequent regrowth. The effect which pyrogenic trace gas emissions have on the global atmosphere is illustrated by the annual accumulation of ozone-rich air in the troposphere over the subcontinent during the fire season (Fishman *et al.*, 1991, Thompson *et al.*, 1994). Preliminary calculations suggest that one sixth of the global tropospheric ozone production occurs in smoke plumes originating from African savanna fires, and a similar proportion of the global production of the tiny particles known as aerosols. Aerosols have a role in cloud formation and modify the optical properties of the atmosphere. Part of the aerosol is elemental carbon, which ends up in the soil and ocean and is effectively removed from the biosphere.

Vegetation fires are not the only source of biomass burning in Africa. Fire is also part of many agricultural practices, including the burning of residue in cane fields, and traditional ash-fertilisation (chitemene) systems in Central Africa. As in other moist tropical regions, slash-and-burn agriculture at the forest/savanna boundary has resulted in a broad zone of mixed remnant forest patches and derived savannas. A large part of the African population depends on biomass as an energy source, either in the form of fuel wood, or as charcoal. The sustainable use of biomass fuel has no impact on atmospheric CO_2 accumulation, but where the rate of wood harvest exceeds the rate of wood regrowth, there is a net emission of carbon to the atmosphere.

Other processes in African savannas apart from fire also have significance for the global atmosphere. About 2 % of biospheric carbon is stored in African savannas, and about 10 %

of global net primary production occurs there (Scholes & Hall, 1994). Biogenic trace gas emissions also occur as by-products from ecosystem processes, generally mediated by microorganisms. For instance, NO and N_2O are produced during microbial inorganic nitrogen transformations resulting from the mineralisation of organic matter. The vast extent of savannas means that even small emissions can be globally significant. Non-methane hydrocarbons, such as isoprene and monoterpenes, volatilise from the leaves of savanna plants. Methane is produced as a by-product of enteric fermentation in domestic and wild mammals, and also in the guts of termites. On the other hand, well-drained, undisturbed savanna soils may consume more methane than they produce (Seiler *et al.*, 1984).

The fluxes are not exclusively in the direction of the atmosphere. The wet and dry deposition of nitrate, ammonium and sulphate is a significant source of nutrient input to savanna ecosystems, as is the biological fixation of nitrogen by symbiotic and free-living bacteria (Scholes & Walker 1993).

The Ecology of African Savannas

Most non-industrial trace gas and particulate emissions from Africa originate from savannas. This reflects the widespread occurrence of these ecosystems in Africa, which occupy approximately half of the land surface, and the prevalence in savannas of processes producing emissions; for example, biomass burning, herbivory and termite activity. The definition of savannas adopted here includes all those tropical African ecosystems in which both grass and trees co-occur under a seasonally alternating wet-dry climate. The African savannas do not constitute a single homogeneous ecosystem type. At a minimum, two broad classes of ecosystems, differing in composition, structure and functioning, can be recognised.

Broad-leafed savannas, alternatively known as moist dystrophic or infertile savannas, occur on the ancient erosional surfaces that form the central plateaux of the African continent. They occur most frequently on nutrient-poor, well-drained, acidic soils derived mainly from acid, crystalline, igneous rocks of the Basement Complex. Because of the higher altitude of the plateaux, their climates are generally cooler and wetter than lower lying more recent erosional surfaces at the same latitude. The extensive miombo woodlands of Central Africa, dominated by the genera Brachystegia and Julbernardia are examples of this type of savanna.

Fine-leafed savannas, also known as arid eutrophic or fertile savannas, occupy the lower, younger surfaces, including valleys of the major rivers. The underlying soils are relatively base-rich in comparison to those of the higher plateaux, and have predominantly loamy or clayey textures. The Acacia-dominated thorn woodlands are an example of this type of savanna.

The broad distribution of these two generalised savanna types is shown in Fig. 1, while some of the pervasive ecological differences between them are summarised in Table 1. These differences affect the kinds and amounts of gaseous and particle exchange between the savannas and the atmosphere.

This conceptual model of savanna structure and function is derived largely from research in the floristically similar southern and East African savannas. West African savannas, while subject to the same functional constraints, differ in a number of respects. Although the same plant families and subfamilies predominate in the vegetation, there are clear floristic differences between the western and southern savannas. Furthermore, the vegetation has been more extensively modified by people and their livestock in West Africa. In the wetter areas of West Africa much of the savanna-type vegetation is derived from lowland tropical forest, some recently and some a long time ago. The older landscape erosion surfaces are less well preserved in West Africa than in Central Africa, so that the various savanna types are distributed principally in relation to a marked latitudinal rainfall gradient between the coast and the Sahara. The growing season is shorter than in southern or East Africa for the same mean annual rainfall. Consequently, grass production per unit of rainfall is lower and, in the drier regions, dominated by

annual rather than perennial grasses. Despite these differences, the Sudano-Guinean savannas of West Africa are functional analogues of the southern broad-leafed savannas, whereas the Sudano-Sahelian savannas are equivalent to fine-leafed savannas.

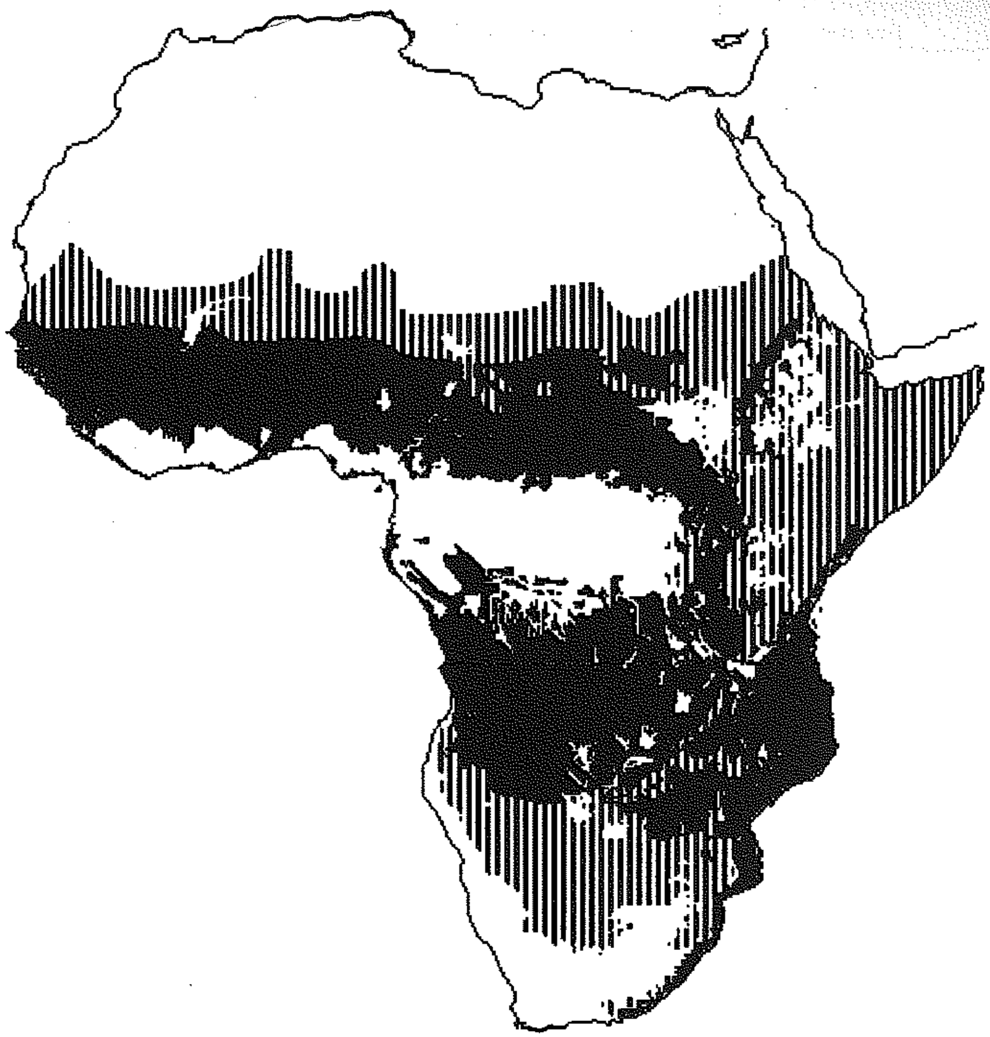

Figure 1. The distribution of broad-leafed and fine-leafed savannas in Africa. The dark-shaded areas are broad-leafed, nutrient-poor, moist savannas, and the striped areas are fine-leafed, nutrient-rich arid savannas. This map has been derived from White (1980) by reclassifying the woodland and wooded grassland map units into one or other of the two savanna classes according to the dominant tree species.

Table 1. A comparison of features of the two broad categories of African savannas. These are general characteristics, to which there are specific exceptions.

Feature	Broad-leafed	Fine-leafed
Age of erosional surface	Ancient	Recent
Parent material	Acid crystalline igneous rocks Aeolian sands Sandstones	Basic igneous lavas Mud- and silt-stones Limestones
Phosphorus availability	Low	Moderate
Dominant clay minerals and CEC per unit clay	Kaolinite, iron oxides (low CEC)	Montmorillonite (high CEC)
Mean annual rainfall	600-1500 mm	400-800 mm
Dominant tree family	Caesalpinaceae (wet) Combretaceae (dry)	Mimosaceae (dry) Burseraceae (v. dry)
Dominant grass subfamily (and tribe)	Panicoideae (Paniceae Arundinelleae Andropogoneae)	Arundinoideae (Aristideae) Chloridoideae Panicoideae (Paniceae)
Mean tree leaf nitrogen content at maturity	< 2.5%	> 2.5%
Grass nitrogen content at senescence	< 1%	> 1%
Mycorrhizal associations and biological N-fixation	Predominantly ECM Low N-fixation	Predominantly VAM Moderate N-fixation
Main anti-herbivore defence mechanisms by trees	Chemical (mainly polyphenols especially condensed tannins)	Structural (mainly thorns)
Tree leaf size	2-10 cm	0.1-1 cm
Grass growth form	Bunch (caespitose)	Creeping (stoloniferous)
Large mammal herbivory	Low (5-10%)	High (10-50%)
Insect herbivory	Episodic, mostly of woody plants by lepidoptera larvae	Seasonally recurrent, mostly of grass by grasshoppers & harvester termites, also episodic by locusts
Fire fuel load	High	Low
Fire frequency	Annual-triennial	Quintennial or longer

There are some savannas with features that are intermediate between these two main savanna types, or do not fit comfortably into this generalised scheme at all. For instance, the functional relationships of the extensive Colophospermum mopane woodlands (known in vernacular as mopani) of southern Africa are still unclear. They seem to be functionally more closely related to the arid, nutrient-rich, fine-leafed savannas, despite the dominance of the tree layer by a thornless species with largish leaves belonging to the family Ceasalpinaceae.

A central hypothesis of current savanna research is that the differences in form and function between broad-leafed and fine-leafed savannas reflect fundamental differences in the patterns of carbon assimilation, allocation and cycling in relation to other nutrients, principally nitrogen. In natural ecosystems generally, carbon, nitrogen and sulphur are closely coupled during the biospheric part of their cycle, as is phosphorus in phosphorus-poor ecosystems. Whereas carbon has an open cycle, with extensive transfers to and from the atmosphere, nitrogen and sulphur have semi-closed cycles with a much smaller exchange with the atmosphere (Fig. 2). The phosphorus cycle is almost entirely closed.

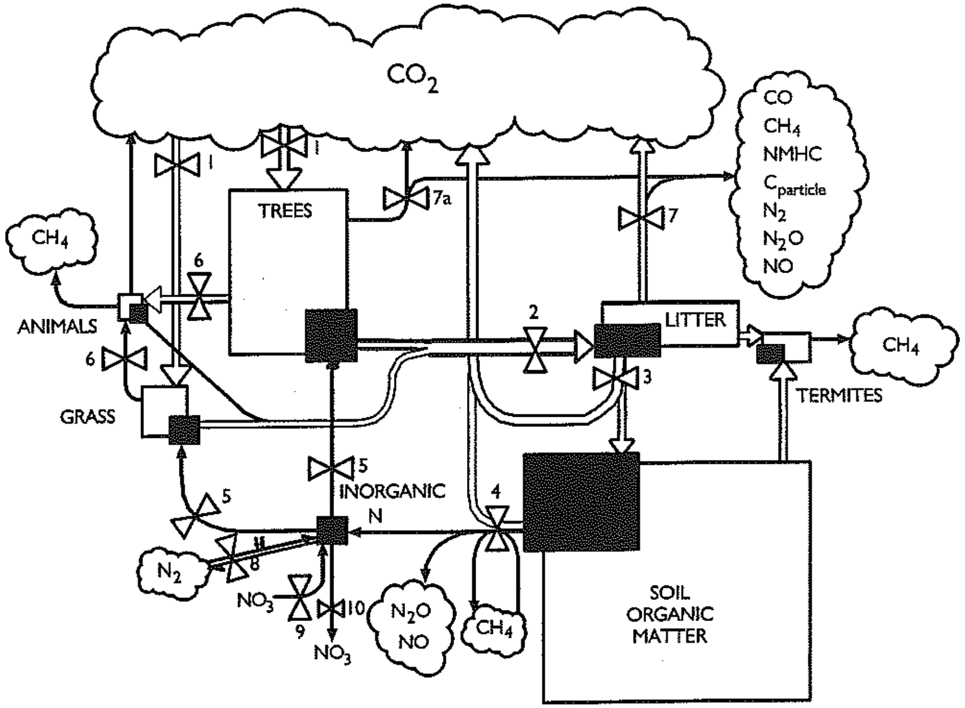

Figure 2. The carbon and nitrogen cycles in a generalised savanna. The relative magnitude of the pools and fluxes differs between broad- and fine-leafed savannas (see Scholes & Walker 1993). The major carbon pools are the clear boxes, and the major nitrogen pools are shaded. The key processes (bowties) are 1. Primary production; 2. Litterfall; 3. Decomposition; 4. Mineralisation; 5. Uptake; 6. Herbivory; 7. Fire (7a. Domestic fires); 8. Denitrification; 9. Wet and dry deposition; 10. Leaching; 11. Biological nitrogen fixation.

The ratios of the major elements in both live and dead organic matter lie within characteristic narrow ranges. Because of the necessary balance between nutrients and carbon in living tissues, the rate of nutrient assimilation can be the process limiting the growth of plants under some circumstances. High carbon:nutrient ratios imply nutrient limitation; low ratios suggest carbon limitation. Carbon assimilation by photosynthesis has traditionally been treated as the rate-limiting step for primary production in savannas. This may be true for arid, nutrient-rich savannas, but there is increasing evidence that the productivity of moist, nutrient-poor savanna ecosystems is limited by the availability of nutrients.

The leaf nitrogen contents, and therefore the instantaneous rates of carbon assimilation, are generally lower in the plants of broad-leafed than fine-leafed savannas. This is offset, however, by higher leaf area indices and a longer growing season in broad-leafed savannas, resulting in an excess of carbon relative to other elements. This excess is sequestered in structural tissues above and below ground, and in carbon-based secondary chemical compounds in leaves. The plants recover a large fraction of the nitrogen from their leaves before shedding them. As a result of the high secondary chemical and low nitrogen content, consumption by herbivores in broad-leafed savannas amounts to a small fraction of the total primary production (Scholes & Walker 1993). The nutrients in the plant tissues are recycled largely through litter decomposition or by burning. Litter decomposition rates are very slow. Fire may speed up the release of nutrients from organic matter, but it also increases the potential for nutrient loss through volatilisation and erosion.

Conversely, in fine-leafed savannas, carbon assimilation is often limited by low water availability. Leaf nitrogen contents are relatively high, in part due to the wide occurrence of species with the ability to fix nitrogen. The shortage of newly assimilated carbon relative to nutrients results in plant tissues with generally lower carbon:nutrient ratios and lower concentrations of carbon-based secondary chemical compounds than those found in broad-leafed savannas. Herbivory constitutes a major pathway for the recycling of nutrients. Fire is infrequent because high consumption by herbivores means less senescent plant material and lower fuel loads. The relatively low carbon:nutrient ratio of both dung and litter ensures rapid decomposition and mineralisation, provided that microbial activity is not limited by low soil moisture levels.

The processes of primary production and carbon allocation are therefore mechanistically constrained by climate and soil type, as well as by the concentration of CO_2 in the atmosphere. The processes of decomposition and mineralisation are relatively insensitive to CO_2 levels. One consequence of this linkage is the prediction that elevated CO_2 will increase primary production less in broad-leafed than fine-leafed savannas, due to greater degree of nutrient limitation on primary production in the former.

We propose that the type, magnitude and pathways of gaseous fluxes to and from untransformed African savannas are predictable from an understanding of their carbon and nitrogen cycles. For instance, in the fine-leafed savannas, methane emissions will be predominantly from herbivores, CO emissions will be low and the soil NO emissions will be relatively high. In broad-leafed savannas, methane and NO will mostly originate in fires, while the soils will be net methane sinks except for emissions from termite mounds. Research into trace gas emissions from Africa needs to be grounded in a thorough

understanding of the biogeochemistry of savannas, and especially in the processes of primary production and decomposition.

Estimation of the fluxes resulting from altered land use patterns in savannas will require an understanding not only of the rate at which these transformations are occurring, but also of the effects of the transformations on biogeochemical cycles. Scenario development will require linkage of the transformation patterns to the underlying social and economic drivers.

An issue which is fundamental to savanna-atmosphere interactions is the relationship between woody cover and grass. Patterns of carbon sequestration, the kinds and extent of herbivory, fire behaviour and chemistry of emissions, as well as the biogenic emission of non-methane hydrocarbons are all controlled by this relationship. The tree:grass ratio in savannas was formerly thought to be stable and predictable, determined at any site by interactions between the prevailing climate and soil physical properties, unless disturbed by human activities. More recently, an alternative view has emerged that the tree-grass relationship in savannas is a disequilibrium system in which domination by trees is prevented by regular disturbance, such as fire and herbivory. In a given environment, a wide range of tree:grass ratios can be found, depending on the disturbance regime. Understanding the processes of establishment, growth, competition and mortality of savanna plants in relation to changes in climate and land use is therefore also a prerequisite for producing a dynamic predictive model of savanna-atmosphere interactions.

Research Issues

Each of the following topics is discussed briefly under several headings. "Key questions" are either issues where the mechanism is generally understood, but more data is needed to quantify the response surfaces, or research areas where more understanding is needed before models and hypotheses can be generated. "Hypotheses" are ideas which are much more specific, but as yet unproven. "Predictions" arise from either the key questions or the hypotheses, and serve to highlight their implications in a global context.

Carbon Sequestration

Savannas have the potential to be either a major carbon sink, or a major carbon source. The switch between source or sink is largely controlled by the fire regime, which is in turn strongly influenced by land use practice in the short and medium term. Three-quarters of the carbon in savannas is stored in the soil organic matter, and most of the rest is in the woody biomass, much of it situated below ground. Detailed knowledge of the size, dynamics, and susceptibility to future change of carbon pools in savannas is sketchy and needs further investigation.

Key questions

1. What determines the structure, composition and productivity of different savannas?

2. What are the current states of carbon and nutrient storage and flux in savannas?

   a) How do these vary in time and space?

   b) How do the patterns of storage, and flux rates and pathways, vary among the different savanna ecosystems (e.g., fine-leafed, broad-leafed, miombo, mopane and Acacia)?

   c) Can any of these systems exist in more than one stable state? If so, what drives the transitions between the states?

3. How will moisture availability, herbivory, fire, land use, and management, alone and in combination, alter carbon storage in savannas under current and predicted future climates?

4. Are African savannas in steady-state with respect to carbon? For example, is the carbon released (mainly as CO_2) by burning reassimilated in the period between fires under current fire regimes?

Hypotheses

The short- to medium-term effect of an increase in fire frequency is to reduce carbon sequestration at a local scale in savannas. This is because the main carbon pools in savannas are the soil organic matter and the tree biomass. The carbon content of the soil of a given savanna is mostly controlled by the magnitude of the organic inputs, which are reduced by burning. Fires also reduce the above ground plant biomass directly.

The long-term, global scale effect of savanna fires is to remove carbon from the biosphere and atmosphere, and sequester it in an extremely resistant form. This is because each fire produces a small amount of elemental carbon, which is virtually inert.

Prediction

The carbon stored in savannas will approximately double if fires are excluded, reaching a new steady state over a period of about half a century (Scholes & Hall, 1994).

Research Strategy

Modelling

The key questions address systems of multi-variate, interacting non-linear processes. Such systems are best addressed through the use of models which represent at least the known basic behaviour and interactions of all the major processes involved. The models in effect become integrative hypotheses, with the model output providing quantitative predictions which can be tested against new observations or independent historical data sets.

A range of generic models exist that address plant population dynamics and ecosystem functioning. For instance, a recent SCOPE project reviewed and compared several models developed for grassland and forest ecosystems (Melillo & Breymeyer, in press). Few of these models have been adapted to savanna ecosystems, which have elements of both grassland and forest function. The proposed strategy for dealing with this section of the research programme is to bring scientists from outside the region, who are familiar with the models together with scientists from Africa, who have the data and knowledge needed to adapt these models to represent savanna conditions.

The objective of this initiative would not only be to develop and run models that apply to savannas, but also to train African scientists in the use of models. This initiative is compatible with the aims and objectives of START, as well as of the Global Change and Terrestrial Ecosystems (GCTE) Long-term Ecological Modelling Activity (LEMA). The development of modelling capacity is seen as a necessary element of global change research in Africa. It is proposed that the development of savanna ecosystem models should be a priority task of LEMA in southern Africa.

Data collation and synthesis

Much is already known about aspects of the functioning of savanna systems, as a consequence of national research efforts and the International Union of Biological Sciences

(IUBS) "Decade of the Tropics" programme on Responses of Savannas to Stress and Disturbance (RSSD), but this information is widely scattered through the scientific literature and unpublished reports. A first step is to assemble, evaluate and synthesise this material, not only to identify outstanding gaps in knowledge and understanding, but also to facilitate calibration and testing of the models. The use of existing data is frequently overlooked. A relatively small investment in manpower and materials (literature and database searches, photocopying, interlibrary loans, etc.) could lead to considerable benefit. It will have to proceed in tandem with the modelling effort, to ensure that the most relevant literature is obtained first. The regional scientists, coordinated through START, would be in the best position to undertake this task.

Experiments

Most ecological experiments in Africa (e.g., fire or grazing trials) have investigated the effects of varying single factors one at a time, rather than a suite of factors changing simultaneously. No experiments have yet been carried out to investigate simultaneously the effects of different levels of soil nutrient and moisture availability on biomass accumulation and allocation, herbivory, fire, and nutrient recycling. Such an experiment, although complex in design, execution and analysis, is essential if the interactive effects of these variables are to be fully understood and if the models that address them are to be tested. These experiments need to be of sufficient duration to encompass (a) the interannual and cyclical climatic variation typical of semi-arid regions; (b) episodic phenomena associated with the co-occurrence of infrequently occurring events; and (c) processes which produce effects with a slow response rate.

The issue of the appropriate scale of measurement, and techniques for transforming data between scales, need to be addressed. Most ecological experiments in Africa to date have been done at the scale of a research plot, for obvious logistical reasons, but studies exclusively focused at this scale often miss the larger spatial components of the processes involved. The spatial scale of the proposed experiments will need to be expanded, particularly if they are to encompass the interactive effects of spatially extensive processes such as fire and herbivory.

The main variables that need to be measured in such experiments are above- and below-ground production and biomass of trees, shrubs and herbs (grasses and forbs); the proportion of annual production that is consumed by herbivores, decomposers, and fire; species composition and plant quality; plant and soil respiration; and the size and composition of the soil carbon pool. Stable isotopes of carbon and nitrogen should be measured in key pools to elucidate pathways and rates of turnover.

The collection of this type of data is time-consuming and costly. The explanatory power of the data can be improved by ensuring coordination of experiments between sites, for example, through organising them into networks or transects. The GCTE "Megatransects" activity (focus 1.2) should lead this approach, with strong national participation.

The question of the long-term sequestration of carbon as elemental carbon could be addressed by measuring the concentration of elemental particles in savanna soils in representative regions. Lake sediments provide an opportunity to investigate the evolution of elemental carbon production over geological and historical time scales. The

African Rift lakes provide exceptionally long sediment records. This task should link to studies of the lake sediments proposed by the Past Global Changes Core Project (PAGES), focused on extracting a climate signal.

Biogenic Emissions

Many of the gases produced by vegetation burning are also produced or consumed by biological processes in the soil, vegetation or animals. The emissions resulting from enteric processes in herbivores are by definition "biogenic", but are dealt with separately in this report because of their importance in African savannas. This section concentrates on the emissions from microbial processes in the soil and litter layer. Whereas pyrogenic emissions are sharply concentrated in the dry season, and at any one moment are emitted by localised sources, biogenic emissions occur mainly in the rainy season, and are spread throughout the landscape. Therefore the instantaneous flux rates per unit area are much lower for biogenic than pyrogenic emissions, but the emissions for the whole continent over the period of a year are quantitatively important. The differences in the rate, scale and timing of biogenic and pyrogenic emissions may have implications for the subsequent absorption and transformation of the compounds. Brief, massive episodes may overwhelm the immediate capacity of the system to assimilate or transform the emissions, thereby leading to transport and transformation at distant sites. It is also necessary to know the magnitude of biogenic sources in order to evaluate the significance of pyrogenic and anthropogenic emissions. Finally, a better mechanistic understanding of biogenic trace gas emission processes will make a significant contribution to the understanding of savanna biogeochemistry, which will have spin-offs in the areas of prediction of primary production and forage quality.

Key Questions

1. What are the factors controlling microbial biomass, composition and activity in savannas, and how do they relate to the kinds, amounts and timing of gaseous emissions?

2. What are the relative contributions of above-ground litter and soil processes to the emission and consumption of trace gases?

Hypotheses

Peak microbial activity rates are predictable from the climate, soil type, vegetation type and land use. Short-term changes in microbial activity in savanna systems are driven primarily by moisture availability. In moist soil, the maximum rate of microbial activity is determined by the availability of organic substrate on which they feed. The clay content and clay mineralogy have a strong influence on the amount of organic substrate present and its accessibility to microbes. The vegetation type determines the chemical composition of the substrates. Within a soil type, soil organic matter content is related to mean annual precipitation and land management practices.

Predictions

Biogenic fluxes associated with microbial activity will be strongly seasonal: highest in the early wet season, and lowest in the late dry season. The degree of seasonality will decline with increasing mean annual precipitation.

The emissions of nitrous oxide and nitric oxide, and the oxidation of methane by aerobic savanna soils are predictable from the amounts of ammonium and nitrate in the soil and their rates of formation and interconversion.

Methane fluxes from savannas where termites dominate the decomposition process will be less seasonal than fluxes from savannas with few termites, since termites are active all year round.

Consumption of surface litter by fires or soil fauna (e.g., termites) will not alter the biogenic emissions of methane and oxides of nitrogen substantially. Although consumption of a unit of dry grass by termites or grazers will result in more methane production than if it were combusted, and microbial decomposition of the same material in the soil may even result in net methane consumption, surface litter will remain a minor source of biogenic emissions.

In infrequently-burned areas, the emissions from litter-dwelling microbes will be larger in broad-leafed than fine-leafed savannas, due to the greater litter accumulation in the former. This litter accumulation is both the result of low leaf herbivory, and of the resistance of the leaves to decomposition.

Research Strategy

The research needed to answer these questions requires a combination of laboratory studies, field experiments, and modelling. Laboratory studies would allow the nature of some of the potential constraints on gas fluxes (moisture, temperature, substrate quality, soil pH, texture, clay mineralogy) to be identified, and the form of the response surface to be explored. Net gas fluxes could be quantified in field experiments using flux chambers and micrometeorological techniques. Such studies should be carried out along ecological gradients, such as soil texture, climate and degree of herbivory, and at a variety of scales.

The contribution of seasonal wetlands (dambos) needs to be quantified. Dambos make up a significant fraction of the landscape in moist savanna regions, but are individually too small to appear on vegetation maps. They are frequently the focus of land-use change, either being drained for dryland crop production, or flooded for paddy rice. There is a strong need to develop appropriate and cost effective methods for carrying out these studies, as well as methods for comparing the biogenic processes in different systems. The priority gases are methane and nitric oxide (NO), with nitrous oxide (N_2O) and carbon monoxide possibly important in some circumstances.

The laboratory and field studies need to be complemented by the use of models. Both conceptual and numerical models are required, not only to help guide the empirical studies, but also to serve as a means of integrating the results and predicting likely future

outcomes under various scenarios of land use and climate change. Models could also be used to explore the questions of scale and extrapolation from point-based studies.

The modelling and the experimental studies need to be preceded by a collation, analysis and synthesis of existing data on decomposition, mineralisation and trace gas fluxes in African savannas.

These studies have a number of features in common with other studies in the proposed programme, particularly those dealing with the issue of carbon sequestration. These complementary areas include detailed characterisation of soils (particularly C/N ratios in litter and soil organic matter, texture, and clay mineralogy); the development of a generic soil-water model; the measurement of vegetation production and chemical composition; and the issue of scaling up from point measurements to landscape and regional fluxes in very heterogeneous environments. The Biosphere-Atmosphere Trace Gas Exchange (BATGE) activity should lead this research area. Where appropriate, measurements should preferentially be made within the research site network developed by START and the GCTE Megatransect activity. The biogenic emission studies should link to the pyrogenic emission work undertaken in SAFARI and its successor projects, in order to capture possible interactive effects.

Pyrogenic Emissions

Fire is believed to be the major pathway of atmospheric trace gas emissions from savannas. Large amounts of methane, carbon monoxide, nitrous and nitric oxide and volatile organic compounds are generated by savanna fires, as well as large quantities of aerosols. The convection columns that develop above the fires inject the gases and aerosols high into the troposphere, where they are transported over large distances. The frequency, timing, and intensity of fires are not uniform across savannas. Fires tend to be more common and intense in broad-leafed savannas than in fine-leafed savannas, since in the latter much of the grass fuel is consumed by herbivores. These general observations need to be confirmed and quantified to provide a basis for calculating regional emissions. In addition to vegetation wildfires, domestic fuelwood burning, charcoal manufacture and use, slash-and-burn agriculture and the burning of agricultural residues are all potentially significant pyrogenic emission sources in the region.

Key Questions

1. What are the important sources of pyrogenic emissions, and what is their magnitude, spatial distribution and seasonal timing?
2. What is the fire frequency in different vegetation types and under different management regimes, and how does the area burned relate to inter-annual climatic variability ?
3. How might the pattern and magnitude of pyrogenic emissions change under different scenarios of climate and land-use change?

4. How does the net primary production translate into fuel components in different vegetation structural types, under different fire and herbivory regimes, and under different land uses?

5. How do the amount and quality of emissions depend on the chemical characteristics of various fuels?

6. How do differences in fuel structure (i.e., the size and packing of fuel elements) and moisture content affect fire behaviour and emission characteristics?

7. How can satellite-based techniques for detecting active fires and burnt areas best be validated and used in the estimation of emissions?

Hypothesis

The emissions from savanna fires to the atmosphere depend on the area burnt, the temperature, duration and oxygen supply to the combustion process, the amount of plant material combusted per unit area, and the chemical composition of the material being burnt. Fires burning during the late dry season are generally larger, hotter and burn more quickly than fires at other times of the year. The amount of material available to be consumed by fire increases with the level of herbaceous production, and decreases with the degree of herbivory. Herbaceous production is a positive function of the amount of rainfall, the soil nutrient status and the length of the growing season, and an inverse function of the degree of tree cover. The nitrogen content of the plant material is higher during the wet than during the dry season, and declines faster during the dry season in savannas on nutrient-poor than nutrient-rich soils.

Predictions

Wet season fires will yield higher trace gas and aerosol emissions per unit mass of fuel consumed than dry season fires.

Fires occurring in the dry season following a season (or seasons) of below average rainfall will occur earlier in the dry season and burn less biomass than fires following seasons of above-average rainfall.

The emissions from the domestic use of charcoal and firewood in savanna regions is directly related to human population density and fuelwood availability, but inversely related to the availability of alternate energy sources.

Research Strategy

A major effort is needed to characterise the amounts and kinds of fuels in relation to vegetation structure and composition, rainfall and soil type. A statistically representative sample of savanna sites should be selected to encompass the major savanna ecosystems at a range of fire frequencies. This would provide a testing and training ground for assessing fuels and quantifying fire behaviour, and for measuring the kinds and amounts of emissions associated with various uses of the vegetation. A standardised fuel and fire

characterisation protocol would help in this regard. The network of sites would also provide opportunities for testing existing models of fire behaviour under a wide range of conditions.

Key parameters that need to be established at each site are the fuel loads and their chemical composition and spatial distribution, the rate of decomposition of the litter component, fire intensity and completeness of combustion. The emission factors for representative savannas burned in the dry season are relatively well quantified. Some additional measurements are needed for out-of-season fires and for particular vegetation types: for instance the resin-rich mopani savannas. This component should be included as part of the START programme. The momentum provided by the SAFARI '92 field programme should be harnessed to expand this research direction.

Experiments

A planned programme of controlled burns in a wide variety of sites and seasons is needed in which fuels, fire conditions, and fire behaviour are characterised in detail. Where possible, fires should be coordinated with overpasses of satellites carrying fire-detection sensors, e.g., Advanced Very High Resolution Radiometer (AVHRR) and Defence Meteorological Satellite Program (DMSP). Burn scar identification and area estimation using coarse resolution satellite data needs to be validated using direct observation or high resolution data obtained from sensors such as Landsat Thematic Mapper (TM) and Système Probatoire de l'Observation de la Terre (SPOT).

The exceptionally long record preserved in the sediments of the African Rift lakes could be used to determine the historical fire frequency and its relationship to climate. This relationship could then be used to evaluate whether the current fire frequency is representative of similar climatic periods in the past. This is a task which could be led by PAGES, as part of its proposed studies of African lake sediments (IDEAL).

Land-Use Change

Africa is a continent in transition, not only in economic and development terms, but also in terms of the patterns of land use. Urban populations are expanding, both through intrinsic population growth and through migration from rural areas. Despite this migration, the populations in rural areas continue to increase. More land is being cultivated, and more intensive forms of agriculture are being adopted over wider areas, to meet the needs of this growing population. The result is accelerating land transformation. The effect of macro-economic policy decisions on land use patterns can be dramatic: by creating or removing incentives to use land in a particular way, they alter both the intensity and type of land use.

Land-use change has impacts on pyrogenic, biogenic and enteric trace gas emissions. Consequently, there is considerable overlap between these topics and the broader topic of land-use change. Land-use change has been highlighted in this report as a separate issue because of its importance as a regional process, and its impact on environmental issues unrelated to trace gas emissions.

Land-use changes in the context of African savannas include the clearing of natural vegetation, changes in the species composition and biomass of large herbivore communities, and changes in crop management and pastoral practices. The replacement of natural vegetation by crops is accompanied by changes in the rate and efficiency of nutrient cycling, in soil organic matter levels, and in the kinds and amounts of emissions. The degree of change is affected by crop and post-harvest management practices, such as the burning or grazing of residue and the duration of fallow periods.

Superimposed on these changes is the inherent high interannual climate variability, plus the predicted changes in global climate. In particular, changes in temperature and rainfall regimes and the frequency of extreme climatic events will alter the land-use patterns.

Key Questions

1. What is the current pattern of land use, and how and why is it changing?

2. What are the carbon and nutrient stocks associated with particular land-use systems in the different savanna regions, and how do these compare with those in untransformed savannas in the same region?

3. How does soil organic matter change over time in cultivated lands derived from savannas, under different crop management regimes?

4. What emissions are associated with the input of inorganic and organic fertilisers during cropping?

5. How do the gaseous fluxes change with intensified herbivory , and with replacement of wild herbivores by domestic stock and *vice versa*?

6. How will fire regimes change under increasingly intensive land use practice?

7. How is land use likely to change under altered climate scenarios?

Hypothesis

The proportion of soil organic matter with a turnover time in the order of decades is higher in savanna soils than in either tropical forest or temperate grassland soils, while the proportion of stabilised soil organic matter with a turnover time of centuries is smaller. These differences are partly due to the tendency of savanna soils to be low in clay and dominated by low-activity clay mineralogies, but is also due to the high soil temperatures and the loss of carbon through fires. The high proportion of relatively labile organic matter makes the carbon content of savanna soils very responsive in the short and medium term to changes in land use practice.

Hypothesis

The emission of nitric oxide from well-drained soils occurs as a by-product of the process of nitrification (the conversion of ammonium to nitrate). The same suite of soil bacteria that are responsible for this process are involved in the methane-consuming capacity of the soil. Therefore, NOx emissions will increase with any activity which stimulates nitrification, but net methane emissions increase when this process is suppressed, for instance by the use of artificial fertilisers. The emission of nitrous oxide (N_2O) is low from well-drained undisturbed savanna soils, but will increase in proportion to the inputs of nitrogenous fertilisers in cultivated savanna soils.

Prediction

Biogenic soil emissions of NOx will initially increase following the cultivation of virgin soils, but will decline over time to a level below that of the undisturbed savanna, in the absence of fertiliser inputs.

Hypothesis

The continuing increase in human populations in the subhumid tropics is creating demand for more cultivable land. The major source of this land will be the clearing of forest fringes. Repeated clearing and burning will transform the land into a mosaic of crop patches and derived savanna.

Predictions

The area of savannas will increase at the expense of seasonal and evergreen forest.

Burning to prepare fallow land for cultivation will increase in areas of recent human settlement, but will decline in areas of high human population density as land is brought into continuous cultivation.

Carbon sequestration in areas of high human population density decreases as a consequence of wood harvesting for construction and fuel, and conversion of savannas to croplands.

Research Strategy

Data are needed on the type, distribution, and rate of change of land use; the kinds and amounts of fertiliser application; the numbers and distribution of cattle; and the amounts of fuelwood and charcoal consumed. Spatially-explicit data on human populations and their growth rates, as well as the basic soil, vegetation and climate databases already mentioned in other parts of the research plan, are needed to interpret and extrapolate the land-use change data. Much of this information probably already exists, but urgently needs collation and synthesis. This will define the gaps that need to be filled through further research and experimentation. Trace gas emission studies in Africa need to address agro-ecosystems as well as natural ecosystems.

There is an urgent need for regional, up-to-date information on land-use and land cover. The first step should be the collation and evaluation of existing information. In most cases these data exist at a subnational or national level. A truly regional effort will require the use of multi-resolution satellite imagery in conjunction with sample ground data collection. Quantifying the rates of change requires sampling at more than one time. The archives of high-resolution satellite data provide an opportunity for retrospective studies since the mid-seventies.

Data on land-use change on their own have little predictive power. They can be enhanced by being linked to studies of the social and economic processes leading to land use decisions. This will require close collaboration with social scientists. The Land Use / Cover Change (LUCC) project, a joint IGBP/HDP initiative, and the regional START projects, could help foster this kind of interaction.

Herbivory

African savannas support the largest biomass and diversity of wild large mammalian herbivores on earth. These populations are becoming increasingly confined to protected areas. Outside of these areas they are being replaced by even greater numbers of domestic cattle, sheep, goats and camels. The stocking rate for both domestic and wild herbivores is related to climate and soil nutrient status. In general, it increases with increasing rainfall, but above about 800 mm on infertile soils it reaches a plateau or declines, due to the low digestibility of the forage. African savannas can be broadly classified into two groups with respect to herbivory, which generally coincide with the fine-leafed vs. broad-leafed split:

- Heavily grazed systems with low herbaceous biomass and infrequent fires
- Sparsely grazed systems with high herbaceous biomass and frequent fires.

The enteric fermentation process which permits mammalian herbivores to derive energy from complex carbohydrates such as cellulose produces large amounts of methane as a by-product. This methane is vented by the animal, and is a globally significant methane source. The methane emitted per animal increases with body size and the cellulose content of the diet, and depends on the structure and function of the digestive system. Ruminants produce more methane than do non-ruminants (e.g., hind-gut fermenters) of equivalent body size.

Consumption of biomass by large mammalian herbivores largely preempts alternative pathways for emissions. Grazing takes the form of a mosaic of heavily and lightly grazed patches that change progressively in size and distribution over the seasonal cycle. This mosaic pattern modifies the distribution of fire across the landscape. Herbivory by livestock changes the spatial and temporal distribution of nutrients (and presumably thus of emissions as well); these tend to be concentrated in night-time corrals and around waterpoints. Grass production fluctuates widely in response to rainfall variations, whereas herbivory is more constant between years. Therefore herbivory reduces the amount of biomass burned during drought years.

Key Questions

1. How much does herbivory in savannas contribute directly to the regional methane emission, and how is this emission partitioned between different types of herbivores?

2. In what ways does herbivory in savannas indirectly influence gaseous fluxes through modifying standing crop biomass and litter accumulation, thereby altering the frequency, intensity, and timing of fire, and the availability of organic substrates for biogenic emissions from the soil and litter?

Hypothesis

The establishment and growth of young woody plants, and therefore the degree of carbon sequestration, is restricted by herbaceous plants, principally grasses. The direct mechanism is through competition with woody seedlings for water, light and nutrients, and the indirect mechanism is through grass providing fuel for fires which kill the above-ground parts of small woody plants. While the woody plants are within reach of large mammal browsers and mixed feeders, their growth is also limited by heavy browsing. If the woody plants are permitted to become significantly taller than the grass, they are much less susceptible to competition or fire damage, and the woody biomass increases substantially.

Predictions

Persistent heavy grazing, by lowering grass biomass, promotes the establishment of woody plants, and ultimately increases carbon sequestration unless the trees are harvested.

Episodes of woody plant encroachment will coincide with periods when the density of browsers is low.

Hypothesis

Above a certain threshold animal stocking rate, herbivory is unsustainable and a progressive decline in the carbon and nitrogen stocks of the ecosystem follows. Thus although methane emissions from ruminants will increase steadily with increased stocking rate, the fluxes of nitrogen oxides from the soil will increase with increased stocking rates up to the sustainability threshold, but will decrease in the long term as a consequence of the overall decline in soil nitrogen stocks. Persistent heavy grazing accompanied by little browsing and the exclusion of fire leads to an increase in the woody component of savannas. This increases the amount of carbon sequestered in the system.

Predictions

Wild herbivores make a small relative contribution to enteric methane sources at a regional scale, since their biomass density is on average low. Their local contribution can be significant, for instance in the highly-productive wildlife areas of the Serengeti.

The net effect of herbivory is to increase methane emissions, since the fraction of the carbon converted to methane by ruminant digestion is greater than by combustion or decomposition.

Research strategy

The patterns of emission of methane among large herbivores, in relation to differences in body size, digestive anatomy, and fibre content of diet, needs to be quantified and documented. This could involve simply a thorough review of existing literature, but may need to be supplemented by additional measurements of methane production in a larger array of species and under a wider range of dietary conditions and activity levels. These relationships can be used in models to examine the implications for methane emission of changing the numbers, species composition and diet of herbivore communities, including a consideration of the alternate pathways of methane emission (e.g., fire and termites).

A study of the effects of herbivores on vegetation pattern, the extent to which the mosaic of heavily and lightly used patches varies seasonally, and the implications for the pattern and extent of fires across the landscape, would require monitoring grass biomass at a landscape scale, in relation to herbivore densities, plant and herbivore community structure and fire patterns. The measurements would need to be taken at least at the end of the growing season and again at the end of the dry season. This could be done on 10-50 km long transects extending from an area predominantly under wildlife to adjacent communal or commercial ranch land. Such transects could be located, for instance, in the vicinity of the Hwange or Gonarezhou National Parks in Zimbabwe, or the Kruger National Park in South Africa. The vegetation mosaics and fire scars could be monitored using high resolution infra-red aerial photography or satellite imagery.

The influence of large herbivores on woody plant dynamics could be included in the research strategy outlined for the study of carbon sequestration. An analysis of woody vegetation changes on existing grazing experiments could provide correlative evidence.

Ongoing and Proposed International Activities

The following brief descriptions of existing and proposed activities in Africa with a bearing on interactions between savannas and the atmosphere represents the knowledge of those represented at the meeting, and is probably not complete. For full addresses to contact persons, see Appendix 2.

System for Analysis, Research and Training (START)

START represents the response of international science programmes (IGBP, WCRP, HDP) to the clear need for strengthening the regional basis of global change research. START activities include facilitating development of regional research agendas, creating research networks, locating funds and building regional human resources needed to advance the central science agenda of the three sponsoring programmes. The START activities in Africa were launched in November 1992 at a meeting in Niamey, Niger (IGBP 1994). A North African regional committee (NAFCOM), and a Southern, Central and Eastern African regional committee (SAFCOM) were formed at that time. The projects to be undertaken by these committees are still in the formulation stage, but it is essential that regional activities emanating from the established Core Projects of the IGBP interface with and complement START regional initiatives. A coordination meeting is planned for southern Africa in Gaborone in mid-1994.

Contact persons: Zachary M. Kasomekera (chairman SAFCOM), Malawi and
Ebenezer Laing (chairman NAFCOM), Ghana

International Global Atmospheric Chemistry Project (IGAC)

This Core Project of the IGBP has two activities directly relevant to the interaction between African savannas and the global atmosphere.

Biosphere Atmosphere Trace Gas Exchange (BATGE)

Biogenic trace gases were measured in association with the SAFARI experiment in 1992. An experimental programme is planned for September-November 1994, to be based at Nylsvley in South Africa. The focus will be on comparing methods for estimating NO fluxes from a floodplain system, but there is opportunity for associated experiments on other trace gases on five distinct soil and vegetation types (four savannas) as well as agricultural lands.

Contact person: Robert A. Delmas, France.

Biomass Burning Experiment (BIBEX)

The Southern Tropical Atlantic Regional Experiment (STARE) and its sub-projects the Southern African Fire-Atmosphere Research Initiative (SAFARI) and Tropospheric Chemistry Experiment-Atlantic (TRACE-A) aim to understand the origin, transport and conversion of tropospheric trace gases and particles in the area of Southern Africa and the South Atlantic. They began in September 1992 with a series of fire experiments in the Kruger National Park in South Africa, radiosonde measurements in Zimbabwe and dust transport experiments based at Etosha National Park in Namibia, coordinated with an airborne sampling campaign over both southern Africa and the South Atlantic Ocean. Further airborne sampling is proposed for the non-fire season in 1994 (SA'ARI 94), and a second fire-associated southern African experiment in 1995 (SAFARI 95).

Contact person: Meinrat O. Andreae, Germany.

Dynamique et Chimie Atmospherique en Forêt Equatoriale (DECAFE)

The DECAFE project is an ongoing international research activity. Although not an IGBP activity, DECAFE has provided important contributions to our understanding of vegetation / atmosphere interactions in Africa. The overall aim of the DECAFE programme is the study of tropical ecosystems (forest and savanna) on the chemistry and dynamics of the atmosphere at the process level. Through the DECAFE program French, German, west and central African scientists have conducted multidisciplinary research. DECAFE 88 was undertaken in the equatorial forest of Congo. FOS/DECAFE 91 and CHARCOAL /DECAFE 92 were undertaken in the Ivory Coast to determine the emissions from savanna fires and traditional charcoal making.

Contact person: Jean-Pierre Lacaux, France.

Experiment for Regional Sources of Sinks and Oxidants (EXPRESSO).

This proposed experiment, which is being considered for joint implementation under IGAC's BATGE and BIBEX activities, will be based in the Central African Republic, at the interface between the savannas and tropical forests. It will have two field campaigns, one in the dry season (January to February 1996), and the second in the following wet season. It will use three research aircraft to sample the atmosphere over the forest and savanna, and the regional transfers between these biomes. There will be an intensively studied ground station in each, with enclosures, towers and tethered balloons. Its objectives are to quantify the exchanges of trace gases and aerosols between the biosphere and atmosphere in the tropics; to analyse chemical interactions between the savanna and tropical forest; to isolate the roles of meteorological and photochemical processes; to characterise the effects of ecological processes on trace gas fluxes ; and to assess the impact of tropical sources on the global troposphere. The experiment was initiated by NCAR in the USA and DECAFE in France, but is open to other participants through IGAC.

Contact person: Robert A. Delmas, France.

Global Change and Terrestrial Ecosystems (GCTE)

The GCTE Core Project of IGBP has developed the idea of "megatransects" as a way to understand and monitor the interaction between the climate and the terrestrial vegetation. Megatransects are continental-scale networks of study sites, distributed across important environmental gradients. The gradient between the wet tropical forests and the dry sub-tropical deserts is a priority for analysis.

Savannas in the Long Term (SALT)

The SALT transect extends along a gradient of increasing aridity northwards from the forests of the Ivory Coast into the Sahelian savannas of Mali, and westward along a gradient of increasing continentality from Senegal to Niger. It was established in 1991, with participation from six West African countries in collaboration with scientists from many non-African countries. Its objectives are to identify and analyse ecosystem responses to natural and anthropogenic constraints; to characterise savanna-atmosphere interactions; and to integrate ecological processes from local to continental scales. The network consists of eight primary sites and many secondary sites, at which data relating to primary production, carbon, nutrient and water cycling, vegetation structure and dynamics and trace gas fluxes are studied.

Contact person: Jean-Claude Menaut, France

Kalahari Transect

A proposal is currently under development for a transect extending from desert shrubland in South Africa to tropical forest in Zaire. The primary sites would all be located on deep aeolian sand, and would each have a standard experiment, consisting of nutrient and water treatments. Sites paired with this core set could explore the effects of grazing intensity and soil type.

Contact person: Pauline Dube, Botswana.

Savanna Modelling

The GCTE Core Project has a Long-Term Ecological Modelling Activity (LEMA) (IGBP 1992). The purpose of LEMA is to develop the ecological models needed to integrate the research results from different activities within GCTE and other IGBP Core Projects. A series of LEMA centres, distributed around the world, are proposed to act as foci where models can be shared and modified for local used and researchers can be trained and supported in using models. A proposal arising out of the Victoria Falls meeting is that a savanna modelling exercise be established in southern Africa, as part of LEMA with strong links to START.

Models of savanna structure and function will be essential for the development and testing of global change hypotheses and for the extrapolation of research findings. A suite of models, at different scales and with different emphases, will be preferable to a single large model. This activity would be better undertaken in a distributed than centralised fashion, but a LEMA centre will need to take responsibility for coordination. At least three classes of model are needed: individual plant-based stand models for simulating savanna structure and composition; biogeochemical models for simulating production and nutrient cycling; and photosynthetic efficiency models for relating remotely sensed APAR to primary production over broad regions.

Contact person: Hank H. Shugart, USA.

Long-Term Ecological Research Sites

There is a critical need for secure long-term ecological research sites in Africa, to provide the information necessary to develop, calibrate and validate models of ecosystem function and to develop the appropriate tools for monitoring the African environment. The minimum ecological data collected should include community structure and composition, primary production by major component, leaf distribution in space and time, ecosystem carbon and nutrient pools and water and radiation fluxes. This must be accompanied by basic climate monitoring data and land use information. There is not a single site in southern or East Africa which has as its primary mission the collection and maintenance of such data sets, although there are many sites which collect part of this information. It is essential that a small number of representative sites with the institutional capacity and security needed to undertake this task be identified and supported. Some of these sites may coincide with transect sites identified above, and the location of sites should be coordinated with the requirements of the Global Climate Observing System (GCOS) and the Global Terrestrial Observing System (GTOS) (MAB-IGBP 1993).

Contact person: Bob J. Scholes, South Africa.

Data and Information System (IGBP-DIS)

There is a need to develop the means and capacity to manage the acquisition, storage, and retrieval of new data, as well as making existing data sources more readily accessible to global change researchers. There is also a need for improved data communication and exchange. IGBP established a Data and Information System (DIS) tasked with addressing these data and information needs. An early focus of the DIS is to identify and assemble the priority global datasets. Its current activities of relevance to African research include the development of a global AVHRR data set and a global soil pedon data base. A primary focus of DIS is to improve international access to and dissemination of data. It has three activities relevant to supporting a regional research agenda associated with African savannas.

Satellite Data

IGBP-DIS in conjunction with the National Aeronautics and Space Administration (NASA), the United States Geological Survey (USGS), the European Space Agency (ESA) and the National Oceans and Atmospheric Administration (NOAA) are compiling a data base of daily 1 km satellite data from the NOAA-AVHRR. This data initiative started in April of 1992 and will extend for at least two years. Coverage of Africa is being compiled from the satellite tape recorders, the Maspalomas, Niamey, Nairobi and the Hartebeeshook receiving stations. The data are being processed by the EROS Data Center, USA. The data set will contain comprehensive spatial and temporal coverage for the African Continent and is being processed to form a composite vegetation index product.

An IGBP-DIS activity has been established to develop a global land cover data base from this data source (IGBP 1992). In addition to the AVHRR data, IGBP-DIS is brokering the acquisition requirements for high resolution data for the IGBP with the international space agencies and data providers. Reduced pricing for Landsat and SPOT data have already been negotiated for global change research. Some of these data will be acquired for Africa.

Contact Person: Ichtiaque S. Rasool, France.

Fire Information System

Two data gathering efforts associated with fire were identified as being especially important at the IGBP-DIS Workshop on Core Project data requirements (IGBP-DIS 1992). The first was the development of daily fire distributions from satellite data. The second was a compilation of data on emission factors from different vegetation fires. An outline of an information system for providing information on vegetation fires to address various research questions was further developed at the Dahlem Conference on Fire in the Environment in 1992. Elements of such a system are currently under prototype development for southern Africa for the purpose of modelling trace gas emissions. The system consists of a combination of remote sensing techniques for fire detection, modelling of fuel loads, and emission factors determined by field sampling. One primary data set for the information system is daily fire distributions derived from 1 km AVHRR data. In an effort to exploit the global 1 km data base, IGBP-DIS is studying the feasibility of generating a global fire product and Africa has been used as a preliminary test case for AVHRR fire algorithm development. In January 1993 IGBP-DIS held a workshop of remote sensing scientists to establish consensus procedures and algorithms for deriving fire information from AVHRR data (IGBP-DIS 1994).

As part of the prototype fire information system for southern Africa a systematic programme of ground based emission measurements has been initiated to provide characterisation of emission factors for different vegetation types. Emission factors have been obtained from controlled burns in representative vegetation types in southern Africa in 1992 and 1993 (Contact: Darold Ward, USA). However to date there has been no formal activity within IGBP-DIS or IGAC to develop a comprehensive global data base of emission factors.

Further research is required to refine and validate the prototype fire emissions information system for southern Africa, particularly in the area of fuel load prediction and estimation. However the system has the potential for extension to other parts of Africa and the world which experience regular vegetation fires. The need by signatories to the Climate Convention to provide emission estimates for the 1995 IPCC assessment is one of the factors promoting this activity.

Contact person: Bob J. Scholes, South Africa.

Global Analysis, Interpretation and Modelling (GAIM)

The Global Analysis, Interpretation and Modelling (GAIM) Task Force is a cross cutting activity within IGBP with the objective of model intercomparison and development. It has three foci, concerned with carbon modelling from three epochs from prehistory to the present. Modelling net primary productivity (NPP) for the current period is a priority activity for GAIM.

Remote Sensing of Net Primary Production (NPP)

A joint activity between GAIM and IGBP-DIS is to generate a global data base of NPP using coarse resolution satellite data as one of the primary inputs. An *ad hoc* working group has been established and a series of workshops are being held to evaluate the contribution of remote sensing to various production modelling efforts and to outline the research agenda (IGBP-DIS 1994). An international intensive field campaign, Niger Hapex, was undertaken in Niger in 1992 involving several IGBP scientists primarily from the Biospheric Aspects of the Hydrological Cycle (BAHC) Core Project. Part of the field programme was planned to provide validation of the satellite based techniques for driving Production Efficiency Models (PEM's). Further field validation programmes are desirable for different vegetation types in Africa. It is envisioned that with the necessary support it will be possible to generate an NPP data base for Africa. The START initiative, the relevant Core Projects and GAIM could collaborate to refine the modelling for continental scale application and develop a more extensive field based validation of the model results.

Contact Person: Steve D. Prince, USA.

Land Use / Cover Change (LUCC)

A joint Core Project between IGBP and the Human Dimensions of Global Environmental Change Programme (HDP) of the ISSC has been developed to address questions associated with Land Use / Land Cover Change (LUCC) (IGBP 1993). This meeting identified a critical need for basic land cover and land use change information at an Africa-wide scale. This core project is currently in the planning stage and it would be most appropriate to include a regional scale African activity within the programme.

African Land-Use Change

Information on the past, present and future land use distribution is essential to the understanding of many aspects of the interaction between African savannas and the atmosphere. At present this information is only available for certain regions, and is very difficult to access. An activity is proposed consisting of a synthesis of available information at a national level, coupled with the classification of land use and land-use change from high-resolution satellite images and a research activity exploring the use of 1 km AVHRR data for continent-wide land-use classification and change detection. Such a programme is already underway for the humid tropical forests, including those of Central Africa. A wall-to-wall assessment of forest extent and rates of change is being undertaken using Landsat data from the early 1970's, 1980's and 1990's through NASA's Landsat Pathfinder Programme. There is a need for similar assessments for seasonal forest and savanna systems addressing changes in agricultural distribution and type, burning pattern, tree cover over the last twenty years. These monitoring efforts need to be closely linked to studies of the processes involved which clearly necessitates close collaboration

with the social science community. Some of the difficulties of achieving such collaboration were raised at the meeting during the working group discussions.

Contact Person: Chris Justice, USA

Table 2. Summary of ongoing and proposed IGBP research and related activities concerning the interaction between African savannas and the global atmosphere

Topic	Ongoing	Proposed
Pyrogenic emissions	SAFARI 92	SAFARI 95, EXPRESSO DIS-Emission Factors Data Base
Biogenic emissions	DECAFE	IGAC BATGE NO Expt SA'ARI 94
Land Use	DIS-Satellite Data Acquisition	LUCC- African Land Use Change initiative
Fire Information System	DIS-southern Africa Emissions Information System Pilot Study	DIS-Fire Information System
Primary Production	SALT Transect Study	Kalahari Transect Africa Long Term Monitoring Network
Modelling	GAIM- RS/NPP Workshops	LEMA Savanna Model GAIM- Africa NPP Modelling

A Research Agenda

The danger of attempting to prescribe research directions is recognised. The purpose of what follows is not to exclude particular activities, but to coordinate what is already proposed, and to propose new activities to fill critical gaps. The agenda is presented in outline only, since the final form will inevitably be influenced by the availability of funding and people. The activities identified below largely reflect the needs and interests of the IGBP Core Projects and the people present at the meeting. It is recognized that they must be coordinated with and compliment initiatives still to be defined by the regional START programmes and pertinent projects not represented at the meeting.

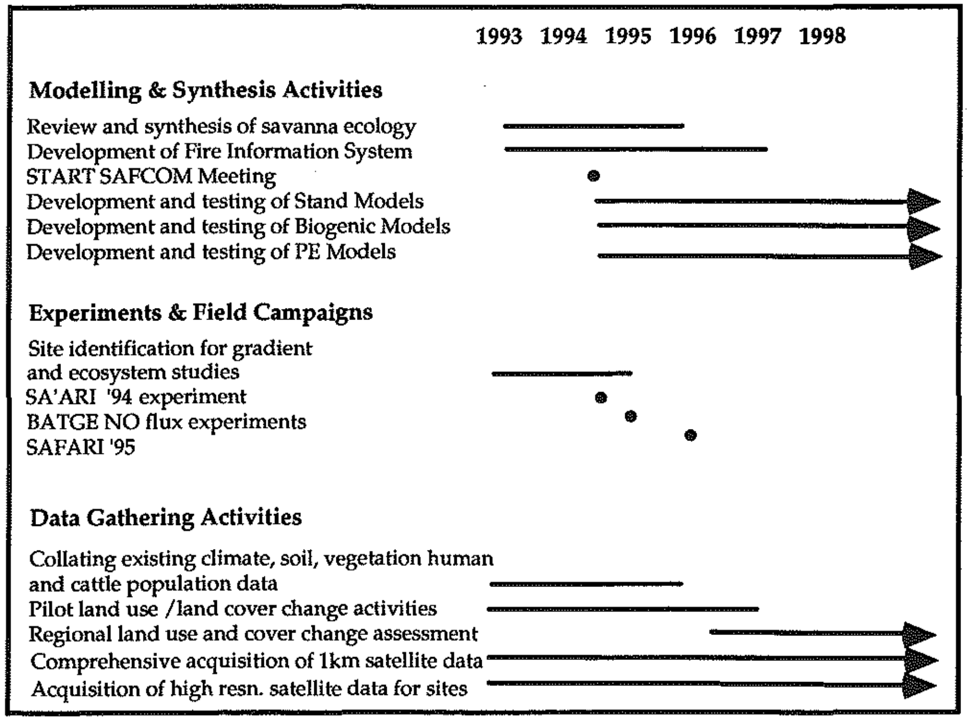

Figure 3. An overview of proposed activities in the field of interactions between African savannas and the global atmosphere for the period 1993 - 1998.

The agenda is a first attempt to translate the key questions identified at this meeting into activities. Where possible the activities should build on existing projects. For example, DECAFE and SAFARI represent starting points for future work on pyrogenic emissions. The key questions raised are largely interdisciplinary and highlight the overlapping interests of the terrestrial ecology, trace gas emissions and atmospheric chemistry communities. Additional inputs will be required from other disciplines, such as the social sciences. For this reason, joint core project activities are highly desirable. Rather than a proliferation of coordinating structures, it is proposed that shared activities should perform the unifying function. For example, SAFARI brought together scientists from IGAC and GCTE, and the megatransects are proposed to combine GCTE, IGAC and BAHC research. The scale of the processes, the common issues, and the availability of human resources, requires a regional rather than local approach. Achieving regionalism will require effort, since funds tend to be allocated on a national basis, even by international agencies.

A three-pronged approach is proposed, consisting of the collation and synthesis of existing data, modelling activities and new experiments and field campaigns (Fig. 3).

The next step in transforming this plan into reality will be for the relevant IGBP Core Projects and the African START committees to further develop and coordinate their regional research agendas. Funding must then be sought to support the proposed activities. This process will have to be driven by individuals and the Core Projects, but it is essential that dialogue be maintained with the other interested parties in order to make best use of the opportunities which develop.

Recommendations

- That the Core Projects of the IGBP coordinate their African research and that the research agenda developed through this workshop serve as an outline for IGBP activities in the sphere of savanna /atmosphere interactions.

- That African scientists be involved at all levels in the planning and execution of the activities. Core Projects need to make a special effort to ensure that this occurs.

- START has an important role in assisting regional scientists to obtain the skills, funds and equipment needed to participate fully in IGBP research, and in establishing collaborative networks within Africa, and between African and other scientists.

- The division of Africa into two START regions should only be an administrative convenience, and should not be allowed to retard the integration of African research along more biologically meaningful lines.

- Major data needs must be satisfied before current ecosystem models can be applied in Africa. These include information on soils, primary production, fuel loads, leaf chemistry and land use and herbivory. Sites dedicated to the collection of this sort of data need to be supported. GCTE should play a lead role in this activity, and the possibility of Global Terrestrial Observing System (GTOS) sites in the region needs to be explored.

- The existing data need to be collated, evaluated and managed. This will be a cost-effective first step. This task will be best accomplished by local scientists who have the insights needed and in most cases access to the data, however they will need technical and financial support. START could play an important role in promoting the national scale implementation of this activity and coordinating national scale data and information into an African wide data base.

- IGBP-DIS should play a role in ensuring that new and existing data are accessible to the research community in general. This will include the development of meta-data structures, archiving and documentation protocols and assistance with the design of project level data and information systems. START and DIS need to coordinate efforts to build IGBP data communication networks within Africa.

- Improved models need to be developed, or existing models modified, for application in savannas. LEMA should take the lead in this activity. A regional center for savanna modelling in Africa could provide a useful focus for the broader development and testing and wider use of these models.

- The Land Use / Cover Change (LUCC) Core Project of IGBP/HDP needs to be active in Africa, and should collaborate as far as possible with other proposed and ongoing land use monitoring activities. National organisations should be both major contributors and beneficiaries of this activity. A LUCC workshop on Land-Use Change in Africa would provide a means to identify on-going activities and to outline the research agenda for the African activity.

- Models and data are needed to address critical management issues in addition to global change questions. For the next few decades, human use pressure will continue to be the major force of environmental change in Africa. START should ensure that the data and analyses developed for global change research in Africa need to available to scientists and agencies dedicated to more immediate problems of natural resource management. New resources need to be identified for global change research, which should not be a drain on the limited regional manpower and funding currently used to address critical resource management issues.

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Appendix 1: Meeting Outline

The workshop was opened by the Deputy Minister for Environment and Tourism for Zimbabwe, Mrs O. Rushesha. Representatives from the Organising Committee then presented the background to the workshop, the objectives of the meeting and the workshop agenda. Professor Rosswall gave a summary on the relevance of the meeting to the Regional START programme and the activities of the Intergovernmental Panel on Climate Change (IPCC).

The workshop was divided into four parts. The first part consisted of a series of review presentations outlining the conceptual models on the major processes and factors effecting regional emissions and remote sensing approaches to developing new data on fire occurrence and fuel load. These reviews were considered necessary given the broad interdisciplinary mix of the participants. The titles and presenters are shown in Table A.

In the second part of the meeting the workshop divided into three sub-groups. The first two groups examined broadly the key processes, the currently available data and new data collection and experimental needs under two categories of major uncertainty, namely primary production (co-chairs: Frost and Prince) and land-use (co-chairs: Scholes and Desanker) A third group was formed to discuss the design and content of a data and information system for regional emissions (co-chairs: Justice and Isichei). Summary report-back presentations and discussion of the current status and the experimental and data needs were presented in a plenary session.

In the third part of the meeting small interdisciplinary groups were tasked with addressing twelve specific questions associated with land-atmosphere interactions (Table B). The response to these questions were presented by group leaders in plenary session. In the fourth part of the meeting four sub-groups were tasked with identifying the key questions, hypotheses and associated experiments under four categories: pyrogenic emissions (Chair - Lacaux) , biogenic emissions (Chair - Miller), herbivory (Chair - Owen Smith) and land use (Chair - Isichei). The key questions, required experiments and data initiatives were then reported back in plenary.

The final session of the meeting was designed to provide the overall research strategy. An overview was presented, which included a description of the GCTE initiative (Shugart) followed by presentations on the current status of the IGBP regional START programme (Kasomekera) and the major field experiments already planned for Africa in the area of land-atmosphere interactions (Andreae, Abbadie, Delmas). A brief outline was then given to the proposed research strategy (Scholes).

Table A. Review papers presented in Part 1 of the meeting.

- Preliminary results of the SAFARI experiments (M.O. Andreae - Max Planck Institute for Chemistry)
- Fluxes between savanna ecosystems and the atmosphere in Africa: potential impact on atmospheric chemistry (J. P. Lacaux - Laboratoire d'Aerologie, France)
- An overview of the relationship of the carbon and nitrogen cycle and trace gas fluxes in terrestrial ecosystems (R. Scholes - Forestek, S. Africa)
- Factors affecting carbon and nitrogen cycling in southern and eastern Africa (P. Frost - University of Zimbabwe)
- Soil biological processes leading to trace gas emissions and consumption in African savannas. (L. Abbadie - CRNS/ENS)
- Pyrogenic emissions from wild fires (D. Ward - US. Forest Service)
- Domestic fuelwood and charcoal use in Africa (A. Riedacker - French Ministry of Cooperation)
- Consumption and metabolism of vegetation by large mammalian herbivores (R. Owen-Smith - University of Witwatersrand)
- Factors governing the distribution and biomass of African wild ungulates (D. Cumming - World Wildlife Fund)
- An analysis of livestock distributions in Africa (P. de Leeuw - ILCA)
- Trends in land and fire use in Africa (A. Isichei - Obafemi Awolowo University)
- The use of remote sensing to determine fire distribution and timing (C. Justice - University of Maryland)
- The use of remote sensing for estimating primary production, phenology and biomass in African savannas (S. Prince - University of Maryland)

Table B. Questions addressed by breakout groups in Part 3 of the meeting.

1. How could we develop a regional / continental emissions model / information system for regional and national level implementation in the next 3-5 years?
2. How would we validate a regional / continental scale emissions model?
3. How can we provide an up-to-date land use inventory for Africa?
4. How can we validate active fire detection and burned area estimate from satellites?
5. How would we develop a model of biogenic fluxes at a regional scale and what information is needed?
6. What field campaign is needed to quantify biogenic fluxes from the region?
7. What information is needed to be able to predict patterns of NPP at the stand, landscape and regional level?
8. What information is needed to be able to predict allocation between trees and grasses?
9. How do we move from NPP to fuel components and fire behaviour and how do we integrate Fire Behaviour Models into a regional scale emissions information system?
10. What information do we need to predict the amount and type of vegetation consumed by herbivores?
11. How does plant quality, abiotic and biotic environment influence decomposition and mineralisation rate?
12. Do we need plant population models to help us with regional emission models?

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Acronyms and Abbreviations

AVHRR	Advanced Very High Resolution Radiometer (a satellite sensor)
BAHC	Biospheric Aspects of the Hydrologic Cycle (IGBP)
BATGE	Biosphere-Atmosphere Trace Gas Exchange (IGAC)
BIBEX	Biomass Burning Experiment (IGAC)
CEC	Cation Exchange Capacity
CEC	Commission of the European Communities
DECAFE	Dynamique et Chimie Atmospherique en Forêt Equatoriale
DIS	Data and Information System
DMSP	Defence Meteorological Satellite Program (a satellite sensor)
ECM	Ectomycorrhyzae
ESA	European Space Agency
GAIM	Global Analysis, Interpretation and Modelling (IGBP)
GCOS	Global Climate Observing System
GCTE	Global Change and Terrestrial Ecosystems (IGBP)
GTOS	Global Terrestrial Observing System
HDP	Human Dimensions of Global Environmental Change Programme
ICSU	International Council of Scientific Unions
IDEAL	Internatinal Decade of East African Lakes (PAGES)
IGAC	International Global Atmospheric Chemistrty Project (IGBP)
IGBP	International Geosphere-Biosphere Programme (ICSU)
IOC	Intergovernmental Oceanographic Commission (UNESCO)
IPCC	Intergovernmental Panel on Climate Change
IUBS	International Union of Biological Sciences (ICSU)
LEMA	Long-term Ecological Modelling Activity (GCTE)
LUCC	Land Use / Cover Change Project (IGBP/HDP)
NAFCOM	North African Regional Committee for START
NASA	National Aeronautics and Space Administration (USA)
NMHC	Non-Methane Hydrocarbons
NOAA	National Oceans and Atmospheric Administration (USA)
NPP	Net Primary Productivity
PAGES	Past Global Changes (IGBP)
RSSD	Responses of Savannas to Stress and Disturbance (IUBS)
SAFARI	Southern African Fire Atmosphere Research Initiative (BIBEX)
SAFCOM	Southern, Central and East Africa Regional Committee for START
SALT	Savannas in the Long-Term (GCTE)
SCOPE	Scientific Committee on Problems in the Environment (ICSU)
SPOT	Système Probatoire de l'Observation de la Terre (a satellite sensor)
START	System for Analysis, Research and Training (HDP/IGBP/WCRP)
TM	Thematic Mapper (a satellite sensor)
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
VAM	Vesicular-Arbuscular mycorrhizae
WCRP	World Climate Research Programme (ICSU/WMO/IOC)
WMO	World Meteorological Organization