THE GLOBAL ENVIRONMENT MONITORING SYSTEM

GEMS
SAHEL SERIES
NUMBER 4

NAIROBI
1988

Inventory and Monitoring of Sahelian Pastoral Ecosystem

ANNEX 4:
SAMPLING THE SAHEL

UNITED NATIONS ENVIRONMENT PROGRAMME
[illegible]OD AND AGRICULTURAL ORGANISATION
GOVERNMENT OF SENEGAL

SAHEL SERIES

1. Introduction to Sahelian Pastoral Ecosystems Project
2. Rainfall in the Ferlo (Sahelian Region of North Senegal) since 1919
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Executive Summary:

The GEMS Sahel Series is a product of the Pilot Project for the Inventory and Monitoring of Sahelian Pastoral Ecosystems. This project was set up to demonstrate and assess the GEMS methodology for ecological monitoring in a West African pastoral ecosystem.

The present document, the fourth in the series, is divided into two parts.

The first part of this report defines terms used in vegetation sampling, and discusses both the general strategies for sampling vegetation in the Sahel and the specific design of a system for the collection of data in the field to describe and monitor plant communities. Its major concerns are with the sound and practical design of sampling strategies, including stratification of the environment for efficient sampling, site placement, the repeated location of the same sampling point, and the correct selection of the method to be used for sampling from among the many alternatives. A large section is devoted to the selection of parameters for monitoring.

The second part examines the results of computer simulations of techniques used for collecting data in the field, including the point centre quadrat, circular plots, and transects.

Global Environment Monitoring System Program Activity Centre
SAHEL Series No 4

Title:
Sampling the Sahel

Author: M. Sharman

Target audiences: Development agencies
Range managers
Researchers in ecological monitoring projects
Remote sensing projects

Objectives:

(1) Define terms useful in ecological inventory and monitoring
(2) Discuss problems in designing a sampling strategy for vegetation with particular emphasis on:
   (a) problems particularly likely to be encountered in the Sahel
   (b) collection of data on grass-layer biomass for calibration of satellite images.
(3) Present and discuss methods applicable to vegetation sampling in the Sahel
(4) Examine use of computer simulation in testing sampling methods

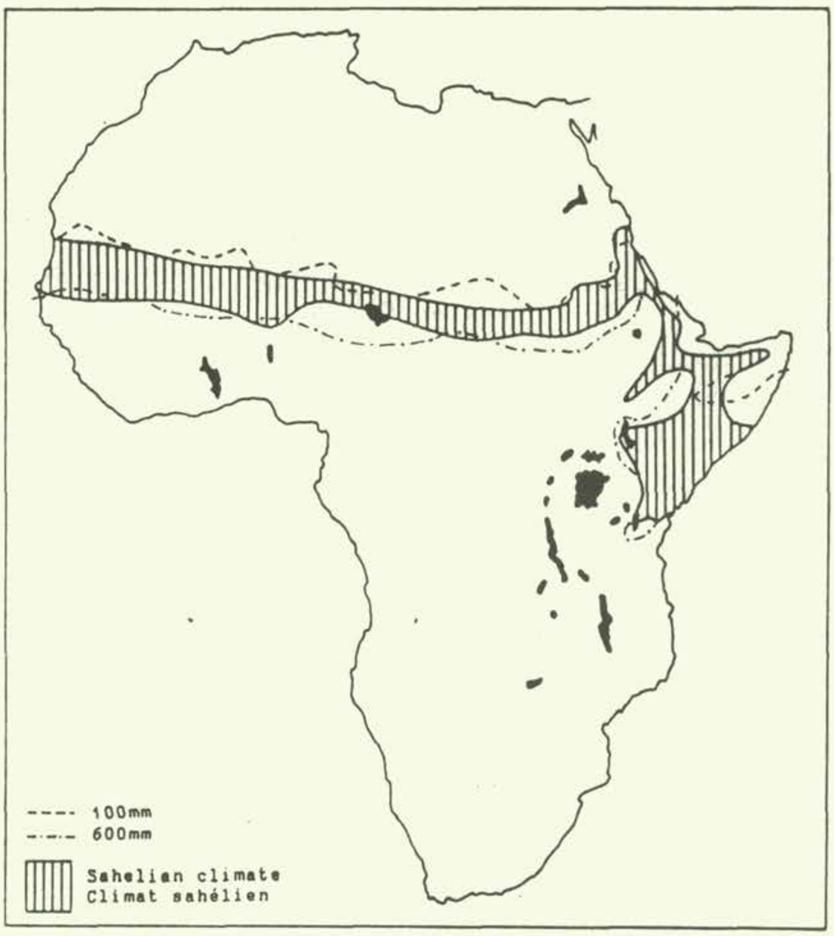
It is remarkable that a science which began with the consideration of games of chance should have become the most important object of human knowledge.... The most important questions of life are, for the most part, really only problems of probability.

Laplace: Théorie Analytique des Probabilités

e.m.u. 1. ecological monitoring unit
2. animal rarely seen aloft

Dictionary of Mythical Beings

Frontispiece: The sahelian zone



Source: Van Chi-Bonnardel R. (1973)
L'Atlas de l'Afrique. IGN, Paris.
Editions Jeune Afrique. Paris.

Preface

From the available data it seems probable that the numbers of domestic stock in the Sahel have reached levels equal to those of the decade before the catastrophic drought of 1968-72. At the same time the condition of the rangeland has improved only slightly, if at all, from its degraded state immediately after the drought. Furthermore, in parts of Africa, extension of agriculture has meant that pastoralists no longer have access to some of their former pastures. If the future of pastoral peoples is to be assured, the condition of rangelands must be preserved and if possible improved. Unfortunately the protection of the pastures poses well-nigh intractable social and complex ecological problems. The ecological problems alone cannot be solved unless the dynamics of the ecosystem are understood, and understanding can only be achieved by approaching the ecosystem as a functioning whole. To this end, the United Nations Environment Programme's Global Environment Monitoring System (GEMS) set up the Pilot Project for the Inventory and Monitoring of Sahelian Pastoral Ecosystems, which was executed by FAO as part of the global network of GEMS monitoring projects.

Objectives of the sahelian monitoring project

There were two major objectives. Firstly, the project was to adapt the standard GEMS ecological monitoring methods to the inventory and monitoring of sahelian pastoral ecosystems. Thus data were to be collected from observations made at three levels (on the ground, from the air, and from satellites), using methods designed to encourage a systems approach in their presentation and use. Secondly, the project was to collect data which would improve understanding of the renewable resources in the world's arid lands.

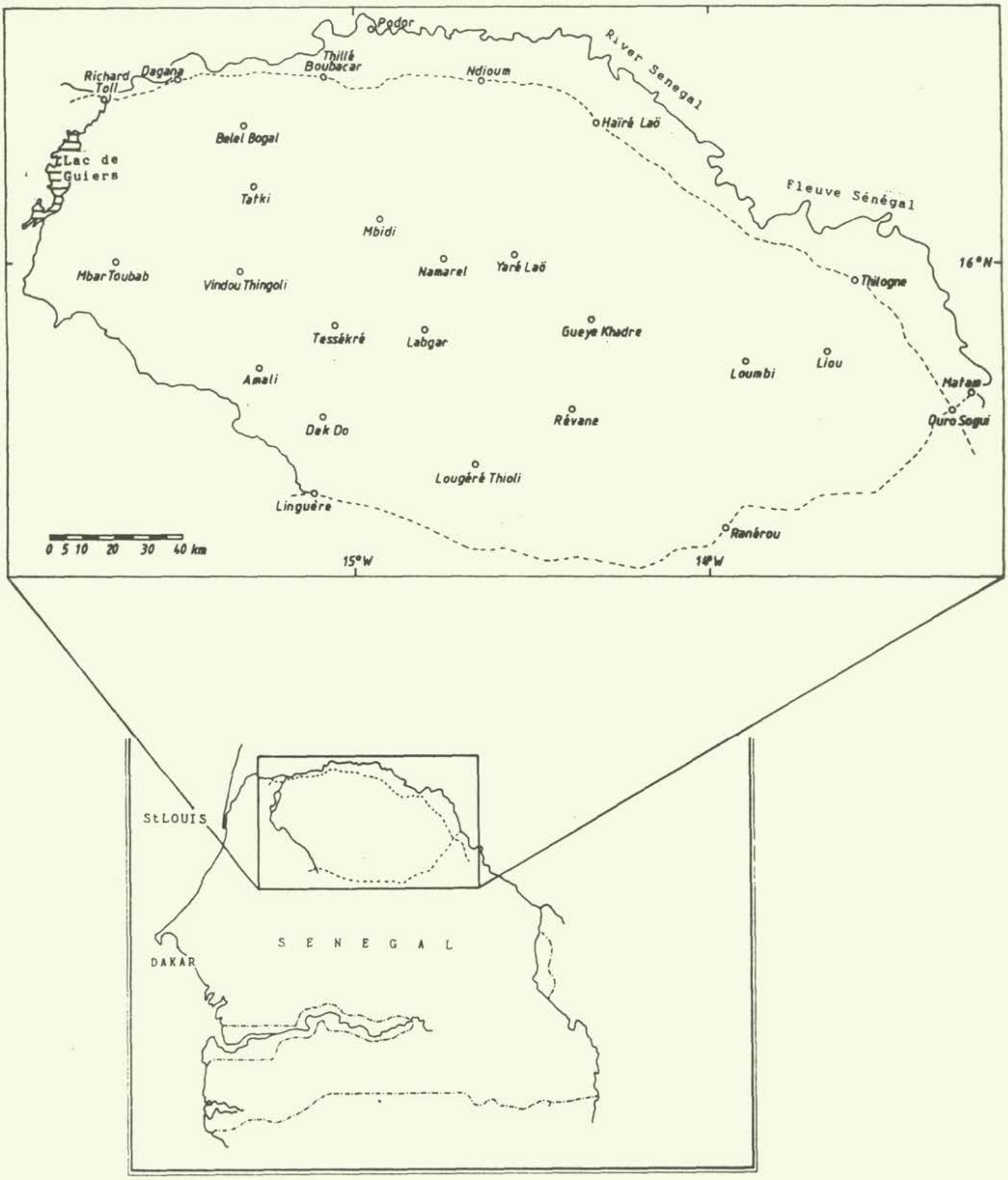
Choice of test zone

The ecology and economy of the north of Senegal is typically sahelian, and the area faces many of the ecological problems that confront the Sahel elsewhere. The zone chosen as a test area for the project, some 30,000 sq km of low-lying pastoral land (Figure 1), is bordered to the west by the shallow Lac de Guiers, to the north and east by the River Senegal, to the southwest by the fossil valley of the Ferlo, ending at Linguère, and to the south by the road between Linguère and Matam (on the River Senegal). This area corresponds roughly with that known traditionally as the Ferlo du nord, or north Ferlo. In the GEMS Sahel Series the test zone is known simply as the Ferlo.

Objectives of this document

To discuss the problems peculiar to the Sahel in designing a sampling strategy for the vegetation, with particular emphasis on the collection of data on grass-layer biomass for the calibration of satellite images.

Figure 1: Location of the test zone of the Pilot Project



Sampling the Sahel

Part I

Part I

1 Introduction

1.1 The United Nations Environment Programme

The United Nations Conference on the Human Environment (Stockholm 1972) made it clear that

"through ignorance or indifference we can do massive and irreversible harm to the earthly environment on which our life and well-being depend. Conversely, through fuller knowledge and wiser action, we can achieve for ourselves and our posterity a better life in an environment more in keeping with human needs and hopes".

In other words, for better or for worse, man has taken responsibility for the wellbeing of the global ecosystem. As a result of the Stockholm Conference the United Nations Environment Programme (UNEP) was established, which in turn set up the Global Environment Monitoring System (GEMS) to monitor the world's natural resources.

1.1.1 The methodology of the Global Environment Monitoring System

GEMS established a methodology which is discussed in detail in the GEMS "Handbook of Ecological Monitoring" (Clarke 1986). In brief, environmental data are collected:

- on the ground, either at monitoring stations or by mobile teams

- from the air, by observers and automatic sensors in light aircraft

- from orbit, by satellite-borne sensors.

Data from these three monitoring levels complement each other, and most ecological monitoring programmes use all three. In particular, ground observations, which are detailed but expensive in terms of the cost per unit area, are frequently used to calibrate satellite images, which while relatively cheap are of little worth without the ground "truth".

1.1.2 Function, objectives, and structure of this document

While the GEMS Handbook of Ecological Monitoring devotes a large chapter to the issues concerning collection of data on the ground, this document is particularly concerned with the design of a system for the collection of data in the field (and in many cases specifically in the Sahel) to describe and monitor plant communities. Its function is therefore to complement and add to the information contained in the Handbook.

Its objectives are: to provide development agencies and the managers of ecological monitoring projects with a general view of the problems to be solved in designing a strategy for collecting ground data; to give range managers and researchers in ecological monitoring projects a source of ideas on which to build a practical programme, and to give remote sensing projects advice on the preliminary design of sampling stations in the Sahel.

The first part of this report contains a discussion of the general strategies for sampling vegetation in the Sahel. The second part examines the results of computer simulations of techniques used for collecting data in the field, including the point centre quadrat, circular plots, and transects.

1.2 Ecological Inventory, Ecological Monitoring

The ecological inventory is designed to collect data which describe the ecology of the area and hence to provide managers with an idea of the options available to them. Inventory, a detailed, geographically based list of climate, soils, plants, animals and human presence and activities, provides information on the status of the system.

Rangelands are ecosystems, and they are therefore in a sense complex living organisms with a behaviour arising from inter-related and interacting processes and components. Ecosystems are constantly changing, frequently as a result of human activity intended to increase pastoral, agricultural or industrial production. An inventory, no matter how detailed, does not therefore tell the whole story.

Ecological monitoring is the continuous collection and analysis of information designed to indicate the trend in the values of selected parameters of a given ecosystem. It thus involves repeated measurement with the aim of recording and detecting change, and is normally focussed on a limited range of elements or indicators in limited subsets of the ecosystem. For example, by monitoring specified elements of the environment before and after new management practices are introduced, the ecological effect of the new measures on those elements can be judged objectively, and if the elements were correctly chosen, the wider ecological effects can be deduced. Unlike inventory, ecological monitoring may tell us little about the status of the entire rangeland.

1.3 The Need for Ecological Monitoring in the Sahel

The Sahel has been subjected to nearly two decades of intermittent drought. The pastures have experienced increasingly intense grazing pressure, frequently exacerbated by the installation of boreholes to provide both human populations and their livestock with water. The capacity of these dry lands to produce is becoming severely strained, and in some areas degradation has progressed to the point where once-wooded land is now sterile earth, loose sand or hardpan.

While governments are aware of these problems there is often little reliable data for them to use in planning to improve land-use. Such data are most efficiently collected systematically by an integrated programme of ecological monitoring.

1.3.1 Priorities of an Ecological Monitoring programme

Since ecological monitoring is designed to detect change, the first, and obvious, objective of an ecological monitoring unit is to decide which events and changes are to be monitored, and in which ecosystem. To do this it must know who will use the data and why these users need this data. Secondly the unit must decide how rapidly the changes must be detected, because this will clearly influence the way in which data are to be gathered, and indeed determines the amount of data that must be collected, as will be seen. Thirdly, the unit must find out which aspects of the ecosystem are likely to be sensitive to the processes which are causing the change, and only then can it concentrate on the fourth objective: the location of monitoring stations and the methods used to collect the data.

In short, the unit must devote considerable effort to the definition and analysis of its data needs. Finally, it must ensure that it has the necessary manpower, equipment and finances to carry out the programme which it proposes, and if not, it must redefine its aims and objectives.

1.4 The need for a statistical approach

By comparison with aerial or satellite-based monitoring, ground monitoring is slow and expensive, and given the extent of the area, it is quite clearly impossible to gather ground data over the whole of the Sahel. Methods which increase the worth and hence decrease the amount of data that must be gathered are therefore highly desirable, since they reduce the cost and the time spent in data collection. The science of statistics has developed with similar cost-worth considerations in view, with the result that correct design of sampling strategy and judicious use of statistics in the analysis of the data can result in a major improvement of the efficiency of work in the field.

In order to be effective, researchers in ecological monitoring projects must not only be familiar with a variety of sampling techniques but they must also have at least a basic understanding of statistics. With the correct statistical methods for the collection and analysis of data the time needed to train field ecologists can be reduced, since expert judgement can be supplemented or even in some cases replaced by mathematical methods (Foran et al 1986). On the other hand, incorrect sampling design or analysis may lead to the following sort of criticism, addressed at a national ecological monitoring unit in an international forum:

The unit's "staff are disturbingly lax in applying statistical principles to sampling design and data analysis. The staff is either naive in its understanding of random sampling and various statistical tests, or it is taking liberties in the use of statistics that cast doubt on the validity of inventory data and even entire inventories" (Klemmedson et al 1984).

To be fully useful, reports should include sufficient information for the interested reader to understand the variability in the data. They should therefore include confidence limits (with significance levels) to mumerical means, and perhaps a section describing possible errors of measurement and their consequences.

1.5 Terminology

1.5.1 Statistical terms

1.5.1.1 Station and sample site

In this report the word "station" is taken to mean a selected location within which are located one or (usually) more "sample sites" at which the parameter(s) of interest are exhautively measured.

1.5.1.2 Accuracy, Bias and Precision

By analogy, an archer is accurate if his or her arrows tend to be near the bullseye, and precise if each arrow lands close to the previous ones, but his or her aim is biassed if each arrow tends to land to the same side of the centre of the target. From this analogy it can be seen that unbiassed, precise estimates are necessarily accurate.

Ideally we would like and expect numeric results to be a faithful reflection of the reality in the field. That is, we would like them to be: (1) accurate, in that they give a result that is close to the true mean value; (2) unbiassed, in that they do not systematically under- or over-estimate the true mean value; and (3) precise, in that repeated measures of the same parameter taken using different samples do not greatly differ from one another.

Unfortunately accurate, precise results are usually expensive, and we are often forced to sacrifice accuracy for precision or vice versa. Accuracy is desireable in inventory, for which the true values are more important than the repeatability of the result, while precision is often more important than accuracy in monitoring, for which the ability to detect change sensitively is usually more important than knowing the true value of the parameter.

1.5.2 Terms relating to the vegetation

Most of the following definitions follow Grieg-Smith (1964) but are adapted to sahelian conditions where necessary:

1.5.2.1 Individual

The "individual" is a single isolated member of a species. Individuals of most sahelian woody plant species and all annual grasses are usually clearly distinguishable. However, several multi-stemmed species, including Boscia senegalensis and Grewia bicolor, are found in the Sahel. The individual is not easily delimited in these species and two observers may make different decisions. For these species the ecological monitoring unit must decide early in the programme how to define individuals objectively in the field. For some purposes it may be appropriate to count the stems at ground level or at a measured distance from the surface. Whatever the criterion chosen, a clear statement of the technique used should be published in a form in which it is of use to other researchers.

1.5.2.2 Density

"Density" is the number of individuals of a species per unit area. For those species in which the individual is easily identified this measure is usually reliably collected by different observers.

1.5.2.3 Measures of Cover

Four measures of the area covered by a plant species should be distinguished:

1.5.2.3.1 Cover

"Cover" is that proportion of the ground that would be shaded by the individuals of the species concerned were they to be illuminated from vertically above, in the absence of any other species above or below.

1.5.2.3.2 Top Cover

"Top-cover" is that proportion of the ground for which the species provides the uppermost layer of cover. This measure, often mistakenly referred to as "cover", is particularly important for all remote sensing applications intended to measure or estimate vegetation parameters.

1.5.2.3.3 Canopy Cover

"Canopy cover" is the cover provided by the leaves and branches of the crowns of woody plant species. The crown of an individual plant is usually regarded as extending over the whole area within its perimiter, even though in reality it may be discontinuous.

1.5.2.3.4 Basal Area

"Basal area" is defined as the proportion of the ground surface occupied by a species, but in woody vegetation is often measured at a specific height above the ground, and then represents the cross-sectional area of the species at that height.

1.5.2.4 Frequency

The "frequency" of a species is the chance of finding the species in a sample of given area and shape in a single trial. Frequency therefore only has meaning for a stated area and shape of sample. Authors often write "frequency" when they mean "percentage frequency".

1.5.2.4.1 Rooted Frequency

"Rooted frequency" is the frequency with which an individual or part of an individual is rooted in the sample area.

1.5.2.4.2 Shoot Frequency

"Shoot frequency" is the frequency with which an aerial part of the plant occurs in the sample area.

1.5.2.4.3 Percentage Frequency

"Percentage frequency" is the percentage of quadrats of a stated size and shape in which a species has been found.

1.5.2.5 Dominance

There are two quite different meanings of the term "dominance":

1.5.2.5.1 Numeric Dominance

"Numeric dominance" is applied to the plant species whose density or (more usefully) cover is highest. In most cases this is the sense meant by "dominance" in ecological monitoring.

1.5.2.5.2 Ecological Dominance

"Ecological dominance" by a plant species implies that the species influences and is little influenced by the other plant species in the area.

1.5.2.5.3 Percentage Dominance

"Percentage dominance" is the percentage of quadrats in which a species is present in greatest amount (see Numeric Dominance).

1.5.2.6 Biomass or weight

"Biomass" is usually taken to mean the above-ground weight of a plant. In this report, biomass refers to the weight of the above-ground part of a non-woody, grass layer plant, or to the weight of the green leaf of woody plants, since that is the part of most interest to ecological monitoring in a pastoral ecosystem. In the former sense it is equivalent to "herbage yield".

1.5.2.7 Vigour

By analogy, the "vigour" of a plant is the equivalent of its state of health. Generally the ecologist is concerned only with the outward appearance of the plant, including traces of disease, damage, or senescence.

1.5.3 Terms relating to the community

Some terms are used especially by plant ecologists and range managers to describe associations of plants and their environment. These terms, most of which are certainly familiar to the reader, include:

1.5.3.1 Species composition

"Species composition" is a list of plant species found in a specified area or stratum. The list is sometimes ordered arbitrarily (eg alphabetically) but more often by rank order of importance, and will often be accompanied by a numeric measure of relative importance.

1.5.3.2 Association

Following the usage of French ecologists, in the Sahel "association" is taken to mean a very small natural unit of vegetation. This usage may unfamiliar to English-speaking ecologists, for whom the term means a well-matured plant community dominated by particular species (eg Acacia-Brachestegia woodland).

1.5.3.3 Community

When applied to vegetation, a "community" is any naturally occurring group of plant species occupying a common environment. Each community is relatively independent of others. Communities, being partly defined and determined by environment, are often very closely associated with landform. This is the case in the Sahel, where small differences in local landform are often most easily detected by their characteristic plant communities with distinct species compositions.

Because of the way it is defined, a community may contain other communities having a more limited environmental range and species composition.

1.5.3.4 Formation

A community which extends over a very large area defined by climate is a "formation". Since the Sahel is frequently defined by the community of plants found there, it is correct to talk of the Sahelian formation of plant species.

1.5.3.5 Rangeland

"Rangeland" is land on which the dominant vegetation is useful for grazing or browsing, and where the ecosystem is managed (if at all) by altering grazing practices rather than by cultivation or reseeding.

1.5.3.6 Climax

In the past "climax" was used to describe a community of more or less stable composition, in equilibrium with existing environmental conditions. Most definitions state or imply that the climax is the final stage of development of the vegetation under existing climatic and physical conditions.

In some definitions of climax the influence of humans on the community is explicitly excluded (eg Trochain 1980 and Le Houérou pers. comm.), which, given the ubiquity of humans and their influence, leads one to doubt the utility of the term.

For this and other reasons the term has fallen into disfavour among some range managers, who now feel that no stable reference point exists (see Ogden 1984, Noy-Meir and Walker 1985, Westoby 1980) either because the state of equilibrium of the system is unknown or because the species composition under any natural regime is apparently slowly but endlessly changing. Since it is unlikely that the field ecologist can define the climax community practically, and since, even if it could be defined, management is unlikely to be able to reestablish climax conditions (Pearson and Thomas 1984), the term is best dropped from the vocabulary of range managers and ecological monitoring units.

1.5.3.7 Ecosystem

An "ecosystem" is the entity consisting of the plants and animals of a locality together with those aspects of their environment with which they are functionally related. "Eco" implies environment, while "system" implies a complex of interrelated and interdependent processes.

No ecosystem is entirely self-contained, since there are inevitably sources and sinks of energy, and frequently of nutrients, external to the ecosystem. In most ecosystems there will be a movement of plant propagels and individuals of some animal species across its boundaries, however the boundaries are defined. The ecosystem is therefore an open system, and the utility of the term depends not on its ability to define the geographic limits of an area, but on its evocation of the universe of processes in which the soils, plants and animals of that area are involved.

1.5.3.8 Sahel

The Sahel is frequently defined by the long-term mean 100mm and 600mm isohyets (see Le Houérou and Grenot 1986). While this definition may appear arbitrary, these isohyets correspond with and delimit the distribution of characteristic sahelian plant and animal species, and characteristic human social systems and production systems, and therefore livestock distribution and land use. However, this definition is not universally accepted, and the interested reader is referred to GEMS (1986a) in which a comparison of the definitions of the Sahel is given in tabular form.

1.5.4 Terms relating to the productivity of the area

1.5.4.1 Condition

The "condition" of the soils, landscape and plant community is conceptually equivalent to the health of a person or animal. The condition of vegetation is closely related to its vigour. The Range Term Glossary Committee (1974) defined condition as the current productivity of a range relative to what that range is naturally capable of producing. Some authors (eg Foran 1986) define condition as the state of degradation of an area and its vegetation as a result of management.

It is a term which depends on many apparently intuitive factors (see Smith 1978 for a discussion), but range managers with considerable experience of the ecology of the area will normally (but not always - see Lamacraft 1978) agree on its condition. Some advance has been made in the establishment of objective means of determining range condition (Beals 1984).

1.5.4.2 Value

The "value" of an area for a particular purpose is the present production of the area relative to its theoretical production. Thus the value of an area for milk production might be classed as excellent, good, fair or poor, depending on the quantity of milk produced relative to the quantity that could theoretically be produced without deterioration of the pastures, that is, under ideal management.

1.5.4.3 Status

"Status" is the current condition of the rangeland or its value for a specified purpose.

1.5.4.4 Trend

"Trend" is the direction of change in status. The terms "down, up and not apparent" are suggested by the Range Inventory Standardisation Committee (1980).

1.5.4.5 Grazing capacity or carrying capacity

"Grazing capacity" is the highest stocking rate that will not damage the vegetation or soils under the given rainfall regime. In the Sahel it varies from year to year with the changes in rainfall and the associated forage production. A working definition for the long-term grazing capacity of rangeland might follow that for crop suitability; that is, long-term carrying capacity corresponds to that provided by the rainfall that can be expected to occur in 80% of the years, or in four years out of five. Recent decline in rainfall in the Sahel (eg GEMS 1986b) means that current long-term grazing capacity is lower than that suggested by long-term rainfall probabilities.

1.6 Constraints on design

Whatever system of sampling is used, it must be designed to overcome the various problems of collecting reliable information in the area. Among these problems are:

1.6.1 The size and accessibility of the area

The Sahel extends for between 5000 and 6000 km across the south of the Sahara in a band 100 to 600 km wide, covering some 3000000 sq km. Roads are generally infrequent and often in poor repair. Access by motorised transport is therefore difficult, even though the land is generally flat and low-lying, and accurate off-road navigation in such featureless terrain presents problems. Landing strips are sparsely scattered.

1.6.2 Heterogeneity of environment

Although the Sahel is in part defined by the vegetation characteristic of the zone (see Le Houérou 1986), its vegetation is nonetheless not distributed homogenously. Most of the grass-layer species are annuals, only growing during the short rainy season, so that there is not only spatial but temporal heterogeneity in plant growth. This heterogeneity is common to many rangelands and forces inventories or monitoring programmes to collect very large datasets for their adequate description (Ogden 1984:766).

1.6.2.1 Scales of spatial heterogeneity

There are three major soil types in the Sahel: the sandy soils, which are found in most of the area; the gravelly or hardpan soils, generally in the south; and the hydromorphic soils near the rivers Senegal, Niger, Logone, Chari and Nile. These three major soil types support distinct plant communities, giving rise to heterogeneity on a regional scale involving some hundreds of kilometers. These zones can easily be detected on Landsat MSS images.

Each of these major zones is itself highly heterogeneous. Thus for example, in the sandy zone there are areas of sand dunes whose vegetation cover is now so thin that the dunes are becoming mobile again, while other areas are flat and covered by open scrub or tree savanna. Yet others are characterised by stabilised sand dunes with open grassland with scattered bushes on the slopes and crests, and clumped woody vegetation in the interdune troughs. Many other types of vegetation are found in the sandy zone alone, giving rise to heterogeneity on a local scale involving some tens of kilometers. These zones can also frequently be picked out on MSS images.

Most of these areas are themselves typically heterogeneous, with, for instance, areas dominated by certain combinations of species separated by a few tens of metres from other combinations, giving rise to distinct plant associations.

Within any apparently homogeneous association are patches, the most outstanding being areas of naked earth, a few tens of centimetres or a few metres across, interspersed among the plants.

1.6.2.2 Causes of spatial heterogeneity

The distribution of plants in the Sahel is influenced by:

- Physical factors such as soil type and humidity, slope, and the local land form

- Climatic factors such as wind speed and direction and the spatial and temporal distribution of rain

- Botanic factors such as the distribution of other plants in the vicinity; thus for example woody plants greatly influence the growth of grass-layer plants beneath them, while the distribution of annual grasses depends in large part on their distribution in the previous year

- Human activities, both direct and through the action of their livestock.

The better the understanding of the causes of spatial heterogeneity in plant distribution, the more efficient can be the sampling design. This would usually mean that as monitoring progresses, and as more is known about the functioning of the ecosystem, the location and number of sampling stations will be changed to reflect sounder scientific design. Unfortunately this may mean that earlier samples are not strictly comparable with later ones. Pilot studies may therefore be necessary in order to design the sampling strategy. The more thought that goes into designing the original distribution of sampling stations, the less the network will be likely to change in subsequent years.

1.6.2.3 Temporal heterogeneity: when to sample?

Plant distribution and densities in the Sahel, especially those of annual grasses, change not only between dry and wet seasons but also from year to year. In the field, grass species are only reliably identified in the growing season, and in some cases only towards the end of the season. If species composition of the grass species is of interest (as it normally would be) a major part of the sampling effort is therefore necessarily compressed into the last month of the growing season. If primary productivity is of interest, at least some biomass samples must be taken at the end of the growing season, thus further condensing the sampling effort into a two- or three-week period whose exact timing depends on the local timing of the rains. The ecological monitoring team must therefore closely follow the development of the plants throughout the area in order to select the correct moment to start collecting data. This in turn implies that the team should have at least one or two experienced members in the field who can alert the rest of the team at short notice.

Real-time meteorological data collected by NOAA or Meteosat satellites may prove useful for deciding when the rains are about to come to an end.

For most inventory or monitoring purposes woody plant species can be inventoried at any time of year, and it would normally be advantageous to carry out this work outside the growing season, so that sampling effort is not diverted from the grasses in this period. However, the ecology of most sahelian woody species is poorly known, and any effort directed at, for example, understanding the relationship between the rate of growth of young plants and the grazing pressure they suffer would imply repeated sampling throughout the year.

Long-term changes in the woody plant community can be monitored by repeated surveys at the same sites at 5 - 10 year intervals. In the Ferlo sites such as those set up by ORSTOM and LAT-Ferlo have profitably been inventoried at irregular intervals after their first census (eg see GEMS 1986e), but such long-interval surveys could become part of a regular programme (eg see Bernes et al 1986).

1.6.3 Manpower

The sampling design must take into account the quantity, quality and mobility of the manpower available for the field work. Given that the analyst rarely has as many samples as he or she would like, the efficient use of manpower is perhaps the major consideration in sampling design. Given also that a very high proportion of the time in the field is spent travelling between stations, it is normally advisable to split up the available manpower into autonomous teams and, for many purposes, to concentrate the effort of each team on a few well-chosen stations which are thoroughly sampled. Autonomy implies independent mobility, which in turn means that the unit must have access to sufficient vehicles capable of off-road all-weather travel.

For most purposes teams of two are sufficient, one of whom must be able to navigate well enough to find the sample sites. One member of each team must thoroughly understand the methods used for collecting the data, and must be familiar with all the species he or she is likely to have to identify, or must be provided with an adequate herbarium and the means to collect and label samples of all unknown plants.

It is impossible to provide any fixed guidelines about the manpower required for a complete inventory or monitoring programme because of the potential differences in aims, areas and environments, and hence in the precision, accuracy and detail required in the study. Nonetheless, specific examples can be given to illustrate the wide range of manpower requirements.

Le Houérou (1980) judges that the work involved in a year-long phytoecological inventory of a million hectares of rangelands would require a team consisting of one ecologist, a part-time soil scientist, one technician, two unskilled laborers, a secretary and a part-time driver, or 2.5 skilled workers per million hectares per year. These requirements, calculated for unspecified rangelands, might slightly overestimate those for the Sahel, a relatively "easy" environment (Le Houérou pers. comm.)

By contrast, the Pilot Project for the Inventory and Monitoring of Sahelian Pastoral Ecosystems, concentrating mainly on developing methods for the monitoring of three million hectares, with greatly reduced detail by comparison with the previous example, required about 1.1 skilled workers per million hectares per year.

The effect of greatly increased scale on manpower requirements is evident by comparing these estimates with those reported by Treadwell and Buursink (1980) for a basic physionomic study of 57 million hectares in Mali. They quote manpower requirements of 9.1 expatriates per year of the project, with an equivalent amount of labour contributed by skilled local staff. This is the equivalent of about 0.3 skilled workers per million hectares per year.

1.6.4 Expense

Since the collection of ground data is expensive, a large part of the budget of the unit will probably be earmarked for financing, training and equipping teams for the collection of data on the ground.

Many attempts have been made to predict the costs of ecological monitoring. No general estimate can be given, since costs vary from project to project for the same reasons as the manpower requirements vary; much of the variability in the cost of inventory or monitoring arises from the differing aims and scales of the projects. However, Welch et al (1980) found that for inventories in Canada there is a minimum cost of about $25000, no matter what the area surveyed, which is spent on salaries, office upkeep and report writing.

The same three examples cited above can be used to show the range of costs for projects with various aims:

1.6.4.1 A million hectares at 1:50000 scale

Le Houérou (1980) estimates that a single detailed phytoecological survey of a pastoral ecosystem with an area of the order of 1000000 ha (equivalent to a square of 100km on a side) would cost about $0.20 to $0.40 per hectare (1980 US dollars). The total cost of this sort of inventory is therefore of the order of a third of a million dollars. Mapping costs a further $0.30 to $0.60 per hectare, and land use planning for the area would cost between $0.10 and $0.20 per hectare. His calculations assume that 50% of this cost is the salaries of United Nations personel, and that the personel spend about a third of their time in the field and two thirds in the office. Ground data for the inventory therefore costs about $0.15 to $0.30 per hectare.

1.6.4.2 Three million hectares at 1:500000 scale

The Pilot Project for the Inventory and Monitoring of Sahelian Pastoral Ecosystems tested various methods in an area of 30,000 square kilometers for five years. The cost was $0.13 per hectare per year of which ground data contributed an estimated $0.08 per hectare per year.

1.6.4.3 Sixty million hectares at 1:5000000 scale

From experience on their project in Mali, Treadwell and Buursink (1980) estimate that a 2.5 year inventory of plant physionomy in an area of 57.5 million hectares cost $0.03 per hectare per year, but this includes the cost of aerial surveys and photography ($90,000) and satellite imagery ($150,000). The remaining $3,560,000 was partly spent on salaries ($2,740,000). The residual $820,000 was presumably spent largely on fieldwork. If a third of the staff time was spent in the field, ground data cost about $0.01 per hectare per year.

1.6.5 Economic effect of increase in detail

The fifteen- to thirty-fold discrepancy between the estimate of Le Houérou (1980) and the costs published by Treadwell and Buursink (1980) presumably stems in part from the reduced detail of large-scale inventories. Le Houérou considered work at scales of between 1:50,000 and 1:200,000, while Treadwell and Buursink were working at 1:500,000. Since halving linear scale clearly implies four times more detail in the resulting maps, and hence at least four times the resolution in the field, so, in the examples cited here, the ten-fold decrease in scale from 1:500000 to 1:500000 implies a hundred-fold increase in detail - and therefore in the cost of ground work.

1.7 Preparation and Follow-Through in Ecological Monitoring

The possibilities for the analysis of the data, and hence the sorts of questions that can be answered, depend on the sampling strategy used to gather the data and on the nature and quality of the samples themselves. In short, "the analysis is only as good as the sample". The analysis itself should obviously be as good as possible, and should be directed at adequately answering the questions which have been asked. This implies that for the ecological monitoring to be of value, its goals must be clearly laid out in advance and that both the sampling strategy and the analytic methods to be used are known before work starts in the field.

Having established the goals of the unit and hence of the data collection, it is often extremely useful to design preliminary checksheets, to check their use with dummy data (or with genuine data collected during a trial), and to carry out the analysis using these dummy data. This exercise will help to point out weaknesses in the checksheet design, redundancy or gaps in the data collected, inadequacy of the sample numbers, distribution or type, and, finally, it will help to show whether the conclusions that may be drawn from the collected and analysed data can in fact be used to fulfill the goals of the unit.

The importance of standardizing forms and methods for data collection cannot be stressed too strongly. The advice contained in the GEMS Handbook of Ecological Monitoring on standardization is reproduced with a commentary in Appendix 1.

An ecological monitoring unit must be equipped and staffed to produce timely reports of its findings. Three sorts of reports concerning ground sampling could usefully be produced: interim reports on the results of the most recent ground-sampling campaign, together with comments, criticism and suggested improvements in methods used; summary reports putting current local conditions into wider temporal and spatial perspective; and integrated reports in which the ground-sampled data are used in the calibration and interpretation of data collected during satellite or aerial reconnaissance.

2 Sampling to what end?

Inventory and monitoring are not the same, and sampling strategies designed for the one may not be suited to the other. In general, inventories require information about a wide variety of parameters over a large area, while monitoring focusses on a few parameters at chosen sites.

2.1 Inventories

Ecological inventories should not be undertaken casually. Inventories are normally more expensive than are monitoring programmes, and their planning needs care.

In an inventory, quantitative estimates or measures are made over a wide area, sometimes with the intention of understanding the variability in some parameter (usually with the aim of improving sampling techniques), but more frequently with the intention of delimiting zones of similar ecology. This implies the need to make inferences about and report on the conditions in the (unsampled) region of similar ecology. A third major use of inventories is to interpret or calibrate satellite imagery; reciprocally, aerial photographs and satellite images are frequently used to generalise the localised findings of an ecological inventory. Ecological zones quantified by inventory would then be used by planners as the basis for management decisions, or by ecological monitoring teams for the stratification and efficient sub-sampling of the zone. Inventories may also be used to derive sets of thematic maps of the area.

Usually the vegetation is not of interest in isolation, and the inventory must be designed to collect data on climate (at least rainfall), soil, available water, the vegetation type and condition, animal numbers and condition, human use of the rangeland and the socio-economy of the area.

The sites of stations for inventory may be selected from existing maps, typically of soil type, vegetation, land use, human ethnic groups, and livestock distribution. Catchment areas and drainage basins are unlikely to be of importance in the Sahel, but political and administrative boundaries may in some cases influence land use. Recent satellite images may be useful in deciding where to locate stations.

2.2 Monitoring

The ecological monitoring programme will often benefit from the prior planning and results of an inventory carried out for that purpose. An ecological monitoring unit will usually make quantitative estimates of various parameters either for comparison with other areas or, more usually, with the same area at a later date. The measurements the unit collects on the vegetation may include the density of a species, its relative frequency, the species composition at the location, the health of individuals, their dimensions, the green standing biomass, and so on.

The criteria used to select the stations and the nature of the stations themselves depend to a large extent on whether the comparisons are to be made between successive visits to the same site or between areas.

2.2.1 Monitoring local changes with time

Changes with time in range condition at sample sites may give direct information about the trend of the ecosystem, and may in some cases indicate its causes. If, for example, all stations in the area show a downturn in range condition, the change is probably associated with changes in the climate, perhaps diminishing rainfall. If, however, some stations show downgrading against a general background of stable or improving range condition, they probably merit closer attention in order to determine the reason for their deterioration.

If the aim of the monitoring unit is to follow changes over time at selected stations, the sites must be chosen and the sampling strategy at each site designed according to the following criteria:

2.2.1.1 Repeated samples of same spot

In the Sahel the inherent spatial heterogeneity of the habitat means that samples taken from two closely neighbouring stations may easily give widely differing results. It is therfore highly uneconomical to attempt to monitor such things as the annual variability in the species composition of the grass layer or the changes (as a result of germination or death) in the number of woody plants at the station by collecting samples from sites whose exact location varies within the station from year to year. Sample sites must be marked in some way so that exactly the same area can be resampled in subsequent years.

2.2.1.2 Choice of ecological strata

Just as some plant species can be used as indicators of ecological change (and especially degradation), so some strata are more sensitive to ecological changes than are others. It is normally useful to concentrate sampling effort in those strata likely to respond clearly to the ecological change being monitored. This may mean that a rather generalised sampling effort becomes more concentrated as the monitoring unit gains experience in identifying sensitive strata.

2.2.1.3 Number of samples

The number of samples that must be collected at any one site depends on the variability of the parameter being measured and on the precision required in the estimate. Clearly, if the measured value of the parameter varies widely between samples, many samples will be necessary before the analyst can make a reasonably accurate estimate of its probable mean value. For any given amount of variability between samples, greater precision can be achieved in general only by collecting more samples.

It follows that the analyst cannot determine the number of samples needed before going into the field and collecting enough samples to give him or her information on the variability in the parameter of interest. Given that inter-annual variability can only be measured by collecting data at yearly intervals, this may mean that several years pass before a realistic decision can be made on sampling intensity.

The statistician must also know what the unit desires to test: thus, for example, different sample sizes will be needed to (a) test for significant differences between mean values of a parameter at different sites (or different years) or (b) to establish confidence limits about a single mean estimate.

Frequently the question will be, in its fullest expansion:

"how many samples must the unit collect at a given station used in the programme in order to show that if a true difference as small as δ exists between the means of samples taken on successive years at the station there is a probability P that the difference will be declared significant at a significance level α?"

This question is best tackled by the statistical technique of analysis of variance.

The ecological monitoring unit must therefore decide on the smallest true difference (δ) that it desires to detect in the values of the parameter on different years at the given station. This is the threshhold beneath which any change in the value of the parameter is considered unimportant - that is, the precision that is needed in the published results. Thus, for example, the initial sampling of species composition of the grass layer may show that this parameter is so variable that changes of less than 50% in the cover of the dominant species cannot be considered significant, because the number of samples needed to detect a smaller change would be too great to be realistic. On the other hand, initial sampling might show that changes of 2% in the reflectivity of sterile soil at the station can be detected with very few samples, because of its low inherent variability from sample to sample.

In the early years of the ecological monitoring programme, it is therefore likely that data are collected and results presented with apparently arbitrary limits of confidence, since the sample size was not large enough (or, rarely, was larger than needed) to provide the limits of confidence needed for the purposes of the unit. Furthermore, several parameters will normally be measured at each sample site. The number of sites will have been determined by considering principally that parameter which the unit has decided to be the most ecologically significant, and the precision of the estimated values of other parameters will tend to be somewhat arbitrary.

Having decided on a threshhold (δ) beneath which changes between one year and the next in the principal parameter are considered unimportant, and having collected enough samples to have an estimate (s^2) of the variance (σ) - and hence the standard deviation (s) - of the values of the parameter, the number of samples needed (N) can be calculated by: (Sokal and Rohlf 1969):

$$N = 2(s/\delta)^2 * (t' + t'')^2$$

where t' is the value from a two-tailed table of t with 2(N-1) degrees of freedom and a probability of α
and t" is the value of t with 2(N-1) degrees of freedom and a probability of 2(1-P). Note that the value 2 in the formula 2(N-1) arises because 2 years are being compared.

Clearly, since values of t' and t" depend on N, which is the number we are trying to calculate, the only way to procede is to substitute for s and δ in the equation and to guess a reasonable value of N in order to look up t' and t". The formula then gives a new value of N, which is used to find new values of t' and t". This iterative search for N continues until the value stabilises. Note that the value of $2(s/\delta)^2$ need only be worked out once, and that it is necessary to know only the ratio of s to δ, not their values.

Cursory study of the table of t shows that the value of t' will be of the order of 2 to 2.5 for a probability of $\alpha = 0.05$, while t" will probably be near 1 for most reasonable P. This means that $(t'+t'')^2$ will be between about 9 and 12, indicating the need for sample sizes two to three times greater than the formula given in (Poole 1974) and quoted in the GEMS Ecological Handbook (Clarke 1986):

$$N = 4s^2/\delta^2$$

2.2.2 Comparison of stations

If the aim of the monitoring unit is to compare two or more stations the choice of site and the sampling strategy differ from those used to monitor local changes with time in the following ways:

2.2.2.1 Sample distribution

The spatial heterogeneity of the Sahel means that short of the uneconomical strategy of measuring the parameter(s) of interest everywhere within the limits of the station, no thoroughly reliable way of comparing sites has yet been found. As is the case in less variable and patchy environments, the best approach is to ensure that the distribution of the sample sites at each station is carefully planned so as to keep the total number needed as low as possible and to give statistically valid and reasonably reliable results. This will normally involve treating each station as if it were made up of a set of gridsquares, and predetermining the location of sample sites within each gridsquare with the help of tables of random numbers.

2.2.2.2 Choice of ecological strata

For most monitoring purposes the aim will be to establish each station in a single identifiable ecological stratum. The intention may be to compare results from dissimilar strata, but it will be more usual to compare similar ecological strata, perhaps subjected to different external influences. Frequently local patchiness will mean that a randomly placed station of more than about a hectare contains more than one plant association (see § 1.6.2.1). For some purposes it may therefore be necessary to select carefully the exact location of the station to include only the desired association.

2.2.2.3 Need for strict criteria for ecological associations

In order to make comparisons between stations in similar areas great care must be taken to describe the ecological associations exactly. This is especially important if comparisons are later to be made with values reported in the literature.

2.2.2.4 Number of samples

As before, the number of samples that must be collected at each site depends on the variability of the parameter and on the precision with which the analyist is to determine whether or not the two sites differ. In order to construct a representative and unbiassed database it will be found necessary to collect a very large number of samples. This is a complex subject whose ramifications are treated in detail in specialised texts (eg Grieg-Smith 1983, who provides a bibliography of some 480 titles). The simplest formula for determining the number to be used is identical to that given in 2.1.3.

2.3 Inferences about a larger region

Normally comparisons between stations or even between years at the same station are of limited interest in themselves but the stations are assumed (or can be demonstrated) to be representative of a larger region of similar ecology. Just as a single sample site within a station is unlikely to be representative of the station as a whole, so a single station is unlikely to be entirely typical of the ecological stratum in which it is situated. Several stations are likely to be needed to categorise the stratum adequately.

2.3.1 Choice of ecological strata

In a pastoral ecosystem such as the Sahel the strata of interest to an ecological monitoring unit are probably those vital to the human population and its livestock. As a initial guideline the unit's sampling effort should be divided in proportion to the importance of the various strata in the local economy, although it may be found later that certain strata thought to be relatively unimportant contain useful indicator species or communities. It will probably prove useful to start by assessing the relative importance of the various strata, and the definitions of the strata themselves, from interviews with the pastoralists.

2.3.2 Need for strict criteria for ecological associations

The extrapolation of the results and the usefulness of the conclusions will depend on the precision with which the strata sampled are defined. Definitions should not depend on vegetation alone but should include information on soils, landform, slope, landuse, and if possible water balance. The definitions will certainly improve as monitoring continues. Data should be handled and stored in such a way that it is always possible to reclassify stations retrospectivly from their original ecological stratum to another.

2.4 Calibration of satellite images

Satellite images provide an inestimable help to ecological monitoring programmes, provided that they can be correctly interpreted. Their uses are very varied, including the monitoring of: climate (WMO/GEMS 1985), forest destruction (Lanly 1982), the extent and variability in the limits of the desert (Tucker and Justice 1986), groundwater (El-Shalzly et al 1977), desert locust breeding (Hielkema 1977), land use (Bodechtel 1986) and more particularly in the case of the Sahel, the monitoring of standing green biomass (GEMS 1986d, Vanpraet et al 1983). In general, the correct interpretation of satellite images requires that data be collected on the ground. Thus, if the images are to be used for monitoring biomass, representative samples must be collected on the ground for the calibration of the images.

2.4.1 Problems of scale: the sample area and the pixel

Satellite images are constructed from regularly spaced picture elements (pixels) whose dimensions depend on the scanner used in the satellite and on any resampling of the raw data carried out before the image is produced. Each image may consist of many hundreds of thousands of pixels, and the dimensions of the scene represented by the image will in general be roughly proportional to the dimensions of the pixel. Thus images with very fine resolution, such as those of SPOT (resolution down to 10m), represent scenes a few tens of kilometers across, while those with a coarser resolution, such as those of the AVHRR carried on NOAA and TIROS satellites (resolution of a little more than a kilometer at nadir), represent scenes a few thousands of kilometers across.

The uses for which satellite images are to be put will determine which type of sensor is applicable. The considerations of scale and frequency of data-capture will play a large part in determining which images to use: monitoring programmes in the Sahel will typically need information on a very wide area, repeated frequently (especially during the growing season), and would therefore find large-scale, relatively coarse resolution images such as those of NOAA's AVHRR ideal for their purposes. Satellite images are not free, but even if they were, such a monitoring programme would probably find that the mass of information included in images of 10m resolution, and the proliferation of the images themselves, was unmanageable. It is perfectly conceivable, however, that such a programme might need detailed images of a few sites in its larger area, and for this, it could well find NOAA images to be useless but SPOT images ideal.

In heterogeneous environments the task of calibrating the image becomes more taxing as the pixel size increases. With very high resolution images the problem becomes one of determining exactly where the ground samples were taken, but since it may be possible to detect such landmarks as the crown of individual trees, this can usually be solved in a manner similar to that used for aerial photographs. With relatively coarse resolution, a single pixel integrates a wide range of conditions. Thus, for example, within a square kilometer of the Sahel there may be extensive regions of naked earth, local patches of relatively abundant growth in micro-depressions, scattered patches of bush, and wide areas of highly variable but generally poor grass production. The problem is to derive a figure representative of the production of the whole square kilometer sufficiently economically that the exercise can be repeated many times in the two- or three-week sampling period, giving results spanning the range of values found on the image.

2.4.2 Use of two or more satellite sensor resolutions

A solution to the problem may be to use two or more sensors, so that local conditions at several widely-scattered stations are first accurately calibrated using images at fine resolution, which are then used in turn to calibrate images at coarser resolution.

3 Stratification

One of the first decisions of the unit is to determine the limits of the region to be monitored. If possible, the limits of the region should correspond as near as possible to the natural limits of an ecosystem, since its functioning is then less influenced by external processes.

Unless the area is extremely small it is impossible to carry out an exhaustive inventory and one is obliged to base conclusions and decisions on samples. Any sampling system is subject to two opposing constraints: the amount of work that can be carried out carefully and the tendency for both precision and accuracy to increase (up to a limit) as the number of samples increases. The limit to the increase is rapidly reached in a homogeneous environment. Unfortunately the Sahel is far from being homogenous, either in terms of the influence of man and his livestock, or in terms of the landform, in which small changes can give rise to quite different vegetation.

The variable of interest is therefore often distributed unevenly throughout the area to be monitored; the zone almost inevitably contains strata which are more homogenous than is the whole zone. In this case it is advantageous to divide up the zone into strata and to sample within the strata thus defined. In the Sahel the stratum is likely to be in some important ways nearly as heterogeneous as the original zone, and it may be necessary to consider sub-strata and so on.

The heterogeneity acceptable within a single stratum depends on the purpose of the study, and on the principles that: (1) data can always be pooled during the analysis but data collected together may be impossible to disentangle, (2) many samples are necessary for an adequate description of each stratum, and (3) the number of samples is limited by the time, the finances and the workforce available.

Correct and intelligent stratification is perhaps the most important part of any soils and vegetation inventory, and hence of monitoring. If monitoring is not stratum-specific it loses much of its utility. The appropriate, possibly livestock-related, choice of strata is therefore essential to the worth and success of an ecological monitoring unit.

3.1 Aids to stratification

3.1.1 Maps

Where available, published thematic maps may be useful as a means of stratifying the zone. In the Sahel these maps will possibly include:

3.1.1.1 Soils

Major soil types of the Sahel are characterised by distinct vegetation associations. A good soil map of the area is therefore particularly useful in selecting, defining and determining the locations of the principal strata.

3.1.1.2 Vegetation types

Where vegetation maps exist, they are in many cases based more or less entirely on soil maps, and their usefulness may be therefore somewhat limited. However, since they map one or more aspects of a variable of prime concern to an ecological monitoring programme, the possibility of deriving useful strata from vegetation maps should not be ignored.

3.1.1.3 Geological maps

Since geological maps describe sub-surface structures they are likely to be less useful than are soil maps for designing sampling strata.

3.1.2 Satellite images

For large regions a preliminary stratification can be carried out with the help of earth resources satellite images. Three current sources of potentially useful images are the Advanced Very High Resolution Radiometer images from the NOAA series of satellites, Thematic Mapper (TM) and Multi Spectral Scanner (MSS) images from the Landsat (EOSAT) satellites, and SPOT images.

3.1.2.1 NOAA images

NOAA AVHRR images can be used to stratify a region by productivity and might be used to help place biomass sampling stations during the growing season in progress. These stations might be arranged such that few samples were taken in the regions of lowest productivity, and situated on a transect aligned in such a way as to cut the greatest possible number of lines of equal production. Alternatively, AVHRR images might be composited across several years to derive a map of mean productivity and its variability. This map could be used to distribute sample stations at higher concentrations in areas of high inter-annual variability.

3.1.2.2 Landsat images

The potential use of Landsat images is perhaps best illustrated by example. Three major zones can be distinguished on MSS images of the portion of the Ferlo region of north Senegal south of the influence of the river: in the north is an area of unaligned curvilinear patches of woody plant growth; in the southwest is a zone of linear, aligned features, where apparently denuded dunecrests are interspersed with wooded interdune troughs; and in the southeast is a largely wooded zone dissected by dendritic valleys where the woody plant communities are relatively dense. Thus these images suggest three major strata, each of which contains two contrasting formations.

Thematic Mapper images, with a resolution of 30m, are capable of resolving fine detail in the zone, and may be suitable for the same sort of stratification as are SPOT images, but with a larger scene.

3.1.2.3 SPOT images

Panchromatic SPOT images give a resolution down to 10m, which makes them invaluable in the stratification of small study areas, such as the region in the vicinity of a borehole or of a reafforestation project. False-colour images, with a resolution of 20m, are particularly useful in stratifying small areas (60km across) on the basis of woody plant canopy cover or, in some areas, on cultivated and non-cultivated areas.

Under some circumstances SPOT images may be of considerable help in stratifying an area on the basis of aspects of human impact, such as by zones influenced by fuel-wood gathering, or those showing heavy use by livestock.

3.1.3 Aerial photographs

Aerial photographs are particularly useful in the subdivision of major strata determined from maps or satellite images. Other uses of aerial photographs are listed in GEMS (1986c). Aerial photos may either belong to a series forming part of a national or sub-national survey, or they may be specifically commissioned for the ecological monitoring of the area.

3.1.3.1 National survey photographs

In many parts of the Sahel the most recent national survey by aerial photographs took place a decade or more ago. Although in much of the Sahel considerable modification of the habitat has taken place in recent years, archival aerial photographs may in many cases still be used for the purposes of stratification. While the species composition of the principal habitat types seen on old aerial photographs may have changed in the interim, it is likely that at least some of the old ecotones still exist, perhaps now delimiting two different biotopes. The worth of such photographs would need to be tested in the field.

3.1.3.2 Specially commissioned photographs

Aerial photography collected and used for the purposes of ecological monitoring is becoming increasingly widespread (eg see Waller et al 1978). A description of one technique of habitat monitoring using aerial photography from low-flying aircraft is given in Clarke (1986).

For ecological monitoring projects in the Sahel, and indeed elsewhere, the use of a properly equipped light aircraft is almost essential. Its additional use for helping to collect information for the stratification of sampling effort and for the selection of the sites for sample stations cannot be too highly recommended. In this respect the use of vertical photography can be invaluable in that proposed sites can be photographed in colour or infrared from several altitudes and using various focal lengths. The resulting prints or slides can then be examined at leisure. Oblique photographs are of more limited use in that the appearance of even a homogenous habitat changes across the scene shown on the photograph.

This method will be most fruitful in combination with the use of satellite images as described above.

3.1.4 Field work

No amount of work on maps or images (or any other aids to remote stratification) can substitute for an intimate first-hand knowledge of the terrain and vegetation, which in any case is necessary to interpret the images, and frequently, to update the legend to vegetation maps. Preliminary ground surveys should normally be planned on the basis of the initial remote stratification. It may become obvious that what appears to be a single stratum on maps or images can usefully be subdivided, and occasionally it may be decided that remotely-determined strata should be pooled as a result of evidence from the ground.

3.1.5 Expert judgement

Some subjectivity is inevitable in a system of stratified sampling. The ecologist depends on his or her experience to judge, depending on the purpose of the study, which parameters should be used to define strata, how much heterogeneity is acceptable within a stratum and exactly where to draw the limits of the homogenous stratum.

The classification of vegetation types in the field is best carried out following a recognised standard, such as the Braun-Blanquet (1964) set of measures and attributes (translated and listed in Clarke 1986).

3.1.5.1 Assessing human impact: the low level reconnaissance flight

Expert judgement is particularly likely to be needed in the assessment of probable human impact on the environment, and hence in the derivation of strata based on human impact. This judgement would probably take into consideration such factors as the distance from the nearest livestock concentration, the mean seasonal size of that concentration, the presence of villages or seasonal camps, and the presence of major livestock trails. Without a specialised study it is difficult to know what relative weight to give to these various factors in order to map integrated human impact. However, low level systematic reconnaissance flights (GEMS 1986c) can be used to provide maps of the distribution and densities of livestock of the area. These maps may be used to stratify the area by one of the principal agents of human impact.

3.1.5.2 JAC: Judgement assisted by computer

Several studies (eg Foran et al 1986, Grunow and Lance 1969) have shown the utility of the computer in the classification of sample plots by range type using various multivariate analysis of simple, permanent characteristics of the plots such as soil type and landform. Where desirable these classifications can be further subdivided by range condition (Bray and Curtis 1957).

Using these techniques it is therefore possible where necessary to gather data at many sites (typically 100 or more) and subsequently to classify these sites into new strata by objective criteria recorded at the sites themselves. The disadvantage of this technique is that many of the sites may fall in strata for which there are too few replicates for the stratum to be sufficiently well defined, and the sample sites whould then have to be discarded. In the work reported by Foran et al (1986) 40% of their initial 260 sites were discarded. Initial stratification of the area, followed by an automated method of classification of the sites placed in the chosen strata, might prove to be both useful and enlightening.

3.1.5.3 GIS: Geographic Information System

The task of stratification is not easy, for the criteria used for defining strata probably vary with each parameter to be measured. A Geographic Information System (GIS) may be of great help in selecting, refining and updating strata.

A GIS may be thought of in some respects as a computerised atlas, consisting of two parts: a store of data, or database, and software to access and manipulate that data. Just as in a paper atlas, the computerised database contains thematic data, derived from various sources, related geographically to the land. Unlike an atlas, the software associated with the database allows the user, amongst other things, to manipulate thematic information from one dataplane by comparing it with data from different planes, to carry out statistical analysis of spatial relationships, or of relationships between dataplanes, and to map original or derived distributions of data. (For a detailed examination of selected GISs, see Tomlinson et al. 1976.)

Suitable models for selecting strata may be set up and tested, the cartographic output being examined by the ecologists and statisticians together, with a view to altering the model iteratively until a satisfactory set of strata is derived.

Needless to say, the GIS is not confined to helping in stratification, but will also prove efficient in much of the analysis and presentation of results. While most GISs are still designed for mainframe computers or large mini-computers, more and more are being marketed for cheaper and smaller machines.

3.2 Constraints on site placement

Stations within strata must be accessible, representative, and capable of being found in the field.

3.2.1 Accessibility

Accessibility in the sandy areas of the Sahel is usually not a problem, since the land is generally flat and the vegetation sparse. Care must be taken to be sure that the site can be reached without crossing deep soft sand or areas liable to become waterlogged in heavy rain. It goes without saying that a compass is essential equipment.

In the gravelly areas off-road access by vehicle is usually impossible, given the density of woody vegetation. Stations must normally be sited close enough to roads or clearings leading from roads to make it feasible to carry the necessary equipment to the station on foot.

The hydromorphic soils are usually cultivated, so that there is potential access by track and path to most areas. If these areas are to be sampled, sites should be chosen to be as near to all-weather roads as possible. However, cultivated areas require specialised sampling techniques not covered here.

3.2.2 Representativity

In order to be certain that the station represents the stratum adequately it is usually necessary to carry out some widespread basic vegetation surveys intended to derive criteria defining the stratum. Several sites are then chosen which appear to the expert eye to be representative. These sites are sampled and the station is placed at that site which best fulfils the criteria previously defined.

The amount of work involved in this procedure will normally mean that it is omitted and stations are simply sited in areas which appear representative. It must be recognised that in this case one cannot be certain that the station in fact represents the stratum.

3.2.3 Finding the site

The Sahel is largely flat and without landmarks apparent to the outsider (which category includes most if not all members of any ecological monitoring unit). The low-lying undulating terrain and the woody vegetation cover combine to restrict the view to a few tens or hundreds of metres in all but a few exceptional places. Unless the ecological monitoring unit has access to satellite-based compasses the most practical method for finding a station is to mark large trees with splashes of paint to signal places to turn, noting on sketch maps (or if possible on aerial photographs) the location of the trees, the colour of the paint and the direction in which to turn. This system occasionally becomes confusing when there are several teams doing independent vegetation surveys in the area, and even more confusing if a marked tree is cut or burned.

Paint splashes should be renewed regularly.

3.3 Within-stratum heterogeneity

Once located, it will be found that much heterogeneity exists at the location selected for the station. Thus, in monitoring grass-layer production, it will be found that samples collected under woody plant canopy, and at two metres and at ten metres from the stem of the plant give consistently different results. In theory it might be considered necessary to stratify within sample sites; however, it will not be practically possible to eliminate all systematic heterogeneity, and the researcher will have to accept the necessity of collecting many samples at each station.

3.4 Number of strata

Having stratified the region on the basis features on maps, satellite images or photographs, it is almost certain that the analyist will have identified too many potential strata for the unit to be able to monitor stations in each. The aims of the ecological monitoring unit should be sufficiently well defined for the analyst to be able either to regroup or ignore some strata in order that the unit can concentrate its efforts on two or three. Usually it will be found necessary both to regroup some and to ignore other strata.

3.4.1 Pooling strata

If strata are pooled it may be necessary to adopt a sampling method which gives results which are not unduly influenced by one of the original strata at the expense of others. Such a method might be the line transect or the line intercept, aligned so that the sample tends to cut through the various sub-strata of the group. For example, the stratum "slope and crest of dune" might group the three original strata "dune crest without woody plants", "dune slope without woody plants", and "micro-depressions" (which normally contain woody plants). Transects would be aligned at right angles to the line of the dune crest, independent of and cutting through the three original strata as they are encountered. This sample design will inevitably result in a large variance between samples in the same stratum. Suitable design of the checksheets on which the raw data are collected will mean that each sample can itself be stratified during the analysis if necessary.

3.4.2 Omission of strata

If, on the other hand, some strata are not sampled, the reports based on the findings should indicate clearly to which strata they apply, and perhaps give a map showing the areas over which the results can be extrapolated.

3.4.3 Division of sampling effort between strata

Frequently the sampling effort devoted to each stratum is in proportion to the importance of that stratum to the ecology and economy of the zone. Thus in a study of the impact of the diet of livestock on the vegetation, the number of samples in each stratum might be in proportion to the proportion of the diet found in those strata.

4 Marking sample points

Just as it is necessary to leave marks to help the field crew find the stations, for most applications sample sites within the station must also be marked.

4.1 Need for marker

For almost all economic sampling strategies designed to provide long-term data it is necessary to sample exactly the same site again and again. This means that the field team must be able to find the sample sites, which in turn means that their exact location must be marked clearly and unambiguously.

4.2 Requirements of marker

The ideal marker is (1) permanent, (2) cheap, (3) easy to construct and transport, (4) easy to install, (5) difficult to remove, (6) unsuitable for use by local people, (7) unobtrusive in the enviromment and unlikely to disturb livestock, (8) incapable of influencing the parameters to be measured and finally (9) easy to find. Given the importance of resampling the same spot, it is to be expected that no matter what marker is used their financial cost and the work involved in installing them will be substantial.

Since some of these requirements are contradictory, it is unlikely that the ideal marker exists. The Pastoral Ecosystems project tried two designs: a steel tube painted red and placed vertically in the soil in a hole made by a trenching tool, and a concrete mushroom, whose stalk flared towards its base, buried so that only the upper part of the cap emerged from the soil. A steel ring was set into the cap to which a cord or wire could be attached.

The steel post was relatively easy to find but many were rapidly uprooted by the herdsmen. This might have been less of a problem had they been more deeply embedded (75cm) with the help of a pick and spade and had a horizontal steel bar been welded to the lower end. The mushroom was difficult to find, was sometimes buried in sand, and was occasionally the subject of considerable destructive effort on the part of the local inhabitants.

A marker used with success elsewhere in the Sahel (Bille pers. comm.) consists of a hole dug near the centre of the sample site. This marker seems to fulfil most of the criteria, except perhaps (1), since it can be filled in; (7), since it might be troublesome to livestock; and (8), since it might well influence the surrounding plant growth.

Requirements (8), that the marker not disturb the parameters to be measured, and (9), that the marker be easy to find, need some elaboration.

4.2.1 Positioning of marker relative to vegetation to be measured

Sites at which woody plants are to be sampled can be marked in the centre of the site, since it is unlikely that any disturbance will extend more than a few centimetres from the marker, unless it attracts livestock or pastoralists. Markers for sites at which grass-layer species are to be sampled must be placed outside the sample site at a known distance and in a known direction. Unless two markers are used at each site this may make the siting of the sample a little less accurate.

4.2.2 Finding the marker

Given the difficulty of finding a small object in a vast wooded peneplain, and the considerable frustration and loss of time (and hence considerable expense) that hunting for it can entail, some thought must go into designing a system for finding the markers. The most obvious method is to provide indications to its location throughout a wide area centred on the marker. A reasonable system is to paint the trunks of trees and large bushes on the side of the trunk facing the marker. These marks should be white (experience shows that white is the most visible colour in a universe of greens, yellows, browns and blacks), cover roughly 200-500 sq cm, and be renewed at each visit. An economic way of doing this zonal marking is to mark only those trees growing in an oriented (eg North-South) 10m-wide strip extending some 100 metres on either side of the marker (Figure 2).

5 Sampling methods

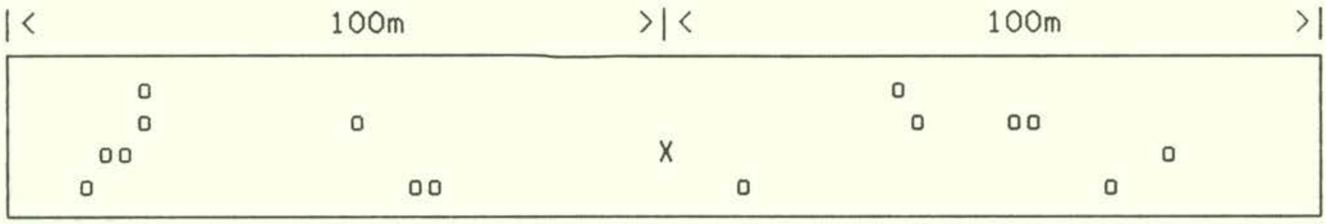
Extensive and detailed discussions of methods used for sampling vegetation are given in Grieg-Smith (1964) and in Mueller-Dombois and Ellenberg (1974). A brief description of selected methods is presented in Clarke (1986). The following discussion concentrates on methods frequently used in the Sahel.

5.1 Point sampling

The point-sample may be collected by a variety of methods to be discussed in the following paragraphs. The principle is the common-sense idea that if a sufficient number of points are recorded at random in a zone divided into distinct categories, the number of points falling in each category is proportional to the relative area of that category in the zone. The point-sample and its variants thus give an unbiassed estimate of cover.

In practice, care must be taken when recording several non-exclusive categories to record all of the categories present at each sample point.

Figure 2: 200m x 10m strip in which principal woody plants are painted



o = woody plant painted white X = marker

For example, when recording plant species, litter and soil erosion, one must not forget to record the state of the litter just because a plant is present.

It is also worth bearing in mind that while point sampling methods tend to be rapid (and unbiassed), the observer's task is made much more difficult the more decisions he or she must make. Thus, deciding that a living plant is present at a point is one thing; deciding whether the plant is mono- or di-cotyledon is another; and recording its species is yet another. The analyst must be aware that there is probably a compromise to be struck between quantity and quality.

5.1.1 Step-count

The simplest and most rapid measure of the proportion of the area covered by a given element (for example species x, or naked earth) is by the step-count method or one of its variations. The observer selects a point in the stratum of interest, sometimes according to a desired criterion, but often at random, picks a direction, and walks in as near as possible a straight line for a predetermined number of steps. The length of each pace should be, as far as is practical, uninfluenced by the habitat through which the observer is walking. Often the observer uses the Roman method of counting paces: steps are scored only as the right foot comes down, so that a pace is approximately one and a half metres long.

Classically, the observer records whether or not the element of interest is under or near the toe of his or her right foot as it touches the ground. The toe of the boot may be notched or equipped with a short pin to aid the observer in deciding where to take the sample. The monitoring unit should make clear what criteria are used to decide what "under or near the toe" means; if the area sampled is small enough, it will almost always sample naked earth, since the basal area of Sahelian annual grasses is usually less than 5% of the ground. A method which gives a result of 95% bare earth for an area of good grazing might well be precise, unbiassed and accurate, but its practical value is perhaps limited. On the other hand, if the area is too large, it may be necessary to provide instructions on how to decide which of several items found "near the toe" to score. Experience in the Western Sahel suggests that the area should probably be about 2cm across for most purposes, and that a small wire loop on the end of a stick may be used to define the area to be sampled. However, this results in a frequency score applicable only to the size and shape of the loop (see section 7.2.2), which the unit may find is difficult to compare or combine with other measurements of the vegetation. If the purpose of the step-count transect is to give unbiassed estimates of cover the sample must be taken at a point - or, if a very small area is sampled, correction factors must be applied (Warren-Wilson 1963).

Percentages are easy to calculate if multiples of 100 paces are counted. Frequently the observer will count 100 paces out, move 50 or so metres to one side, and then count 100 paces back. The observer should beware of walking continuous transects (as it might be, a square consisting of four transects) and treating the sections as independent samples. The habitats at the junction of the transects are oversampled, and the results will be a biassed estimate of the value of the parameter being measured.

5.1.1.1 Variations on the step-count

Most variations on the step-count method are designed to reduce the subjectivity introduced by the observer, who will perhaps unconsciously lengthen or shorten the stride at each step as he or she collects the data. Outstanding among these is a method which uses a wheel with a mark on the rim. A simple device with a "stride" of just under 2.2m is easily made from a bicycle wheel and front fork. This device is most useful in areas in which woody plants are thinly scattered or absent. In wooded areas a tape measure or knotted cord can be laid out.

5.1.1.2 Statistical considerations

Because of the regularity in its design, once the first step on a line has been taken and the first individual has been sampled, the other individuals on the line do not have an equal chance of being sampled. This inherent non-independence of sample points means that the step-count method of sampling can be used to estimate percentages, but cannot strictly speaking be used to examine variability. However, the Sahel is typically so heterogeneous that provided that pace-length is longer than typical patch size of the variable being measured and that the sampling interval does not resonate with some regular ecological pattern, the regularity in the spacing of the sub-samples that make up the transect is probably ecologically (if not statistically) unimportant. The method is likely to produce unreliable results if (a) any of the plants in the habitat exclude other plants, especially of their own species, from their vicinity, or if (b) one of the species present on the transect tends to grow in thickets, as for example Acacia senegal.

The knotted cord variant (and to a lesser degree the tape measure) allows data to be collected at predetermined random intervals, which overcomes the main statistical objection to the method. This allows the the confidence interval about the sample percentage to be found rapidly by using a table of binomial confidence intervals (Snedecor and Cochran 1980). As a very rough rule of thumb, the 95% confidence limits are 10% below and above the observed percentage if 100 steps are counted, 6% if 200 are counted, and 3% if 1000 are counted. As the observed percentage approaches 0 or 100, the lower or upper confidence limit closes in slightly.

5.1.2 Pinframe (Levy and Madden 1933)

This technique (Levy and Madden 1933, Warren-Wilson 1963 etc) is for use on the grass layer only. Typically, a frame holding long pins is constructed so that when the device is set on the ground the pins slope from the frame to the ground, passing through the grass-layer vegetation. Each pin is considered in turn, and the number of times it touches the vegetation is scored. In some habitats (eg the short-grass plains of the Serengeti - McNaughton 1979) the number of contacts is proportional to the biomass in the layer.

The pins must be long enough to pass entirely through the grass layer when sloped in the frame. The spacing between pins should be random, to avoid problems of resonance with the mean inter-stem spacing of the species in the grass layer. The pins should be parallel and their angle of slope must be stated in any quantitative reports, since the number of hits is roughly proportional to the sine of the angle with the vertical. The device may need to include a wind-screen in order to minimise problems arising from movement of the stems.

5.1.3 Plumbline

The canopy of woody plants whose height is less than about 3m can be sampled above a given point by use of a straight rod with a plumbline attached to its upper end. The stick may be graduated by height classes or any other scale in order to record the height of hits or of the upper limit of the canopy.

5.1.4 Moosehorn (Garrison 1949)

Point-intercept measurements of the canopy of larger woody plants can be taken with a device consisting of a mirror allowing the observer to look vertically up without moving his or her head, and a glass plate marked with several points or crosshairs. This device, the "moosehorn", described in detail in Garrison (1949), is levelled with reference to a spirit-level integrated into the apparatus, and is used to count points at which the canopy obscures the sky.

Alternatively a simple device can be constructed for looking vertically upwards, and canopy cover measured from above predetermined points on the ground. This device consists of a cardboard map tube with a mirror fitted at an angle in the base so that the observer can hold the tube vertically and comfortably look through it from the side using the mirror. A plumbline is suspended in the centre of the upper end of the tube (from a thread crossing its diameter). The tube is vertical when the plumb obscures the point of suspension to the observer looking in the mirror. The device is easily converted for looking vertically downwards.

A third method for measuring canopy cover is a 35mm camera pointed vertically upwards. Problems of parallax associated with the height of the canopy above the camera and the angle subtended by a given part of the canopy from the vertical through the camera mean that this device is more useful in monitoring changes from the same point than it is for measuring percent canopy closure. For repeated sampling in a monitoring program the camera must be mounted so that the optical axis is vertical, and so that on each repetition the film is the same distance above the ground and an objective of the same focal length is used. Preferably the sample points are identified in some way which makes it possible to photograph its identifier before taking the sample photographs.

5.1.5 Riflescope (Morrison and Yarranton 1970)

Mueller-Dombois and Ellenberg (1974:89) describe a "promising method" of collecting point samples of both canopy cover and ground cover at the same sample point. This method, devised by Morrison and Yarranton

(1970), involves the conversion of the telescopic sights of a rifle or air-rifle, by means of a prism, into an instrument for looking vertically down or up. The crosshairs give the sample point, and the device is held steady and vertical in a camera tripod. Although this method is initially more expensive than the map-tube, it may prove less cumbersome and more efficient in use. The magnification provided by the sights is a particular advantage.

5.2 Variable Radius Method (Bitterlich 1948)

The variable radius method is used for the rapid measurement of woody canopy cover. In certain habitats, the method is quicker than is the more subjective method of visual estimates of cover (Kinsinger et al 1960). The method depends on the relationship between the angle subtended by a circular object, its distance from the observer, and its area. The observer stands at the selected observation point and counts all woody plants for which the angle subtended by the canopy exceeds a certain threshhold. By knowing the threshhold angle, and assuming that on average, canopies are circular when viewed from above, the resulting number can be interpreted in terms of square metres of canopy cover per hectare.

If the threshhold angle is defined to be .02 radians, the count of plants is numerically identical to the number of square metres of canopy per hectare. This viewing angle is achieved by placing a 2cm-wide window in a card set vertically at the end of a 1m stick (or a 1cm slot in a 50cm stick). The other end of the stick is placed against the cheekbone and the device used to count all canopies larger than the slot in a complete circle around the observer.

In some areas of the Sahel a viewing angle of .02 radians is likely to be so large that very few woody plants are counted. In this case it is advisable to reduce the width of the slot to 1.4cm, and to divide the resulting count by 2 to obtain square metres of canopy per hectare. In other areas nearer plants will obscure the canopies of more distant plants. In the case where this happens to a substantial number of plants the method cannot be used without considerable complicated adjustments to the count, but it may still be possible to use the device for measuring "basal" area (section 7.2.5) at head height.

This method, and others involving the use of angular measurements, is discussed by various authors, including Cooper (1957,1963), Hovind and Rieck (1970), and Mueller-Dombois and Ellenberg (1974).

5.3 Line intercept

The line intercept method (Canfield 1941) has two distinct variants depending on the type of vegetation being measured. In the first, a measuring tape of standard length is laid out and the total length of the element of interest is measured along one side of the tape. In the second, a cord of standard length is laid out and the number of times the element of interest touches or crosses the cord is counted. The first variant is of use with plants which occupy appreciable areas of ground, or for measuring the extent of such things as canopy cover or naked earth. The second variant may be useful for counting linear features such as livestock trails, provided that they are oriented across and not along the line.

The line intercept is generally of little use in the measurement of cover by, or species composition of, annual grass species, whose basal area is relatively so small, and whose aerial parts move in every breeze. Furthermore it is often difficult to use on grass-layer vegetation because (1) the tapemeasure or cord used to define the line tends to lie on the top of the grass-layer plants, (2) it is difficult to make the tape or cord lie straight - although if there is no intention to repeat the measures at the same site at a later date, this is of little consequence, and (3) difficult and frustrating decisions must constantly be made (would this plant touch the line if the cord were lying flat on the ground?). The line intercept is in any case of doubtful worth in the determination of areal extent of features whose outline is highly irregular (see for example section 2.4 in GEMS 1986c), as is typically the case with grass-layer patches.

The line-intercept method is useful in measuring the extent of woody plant cover. The linear extent of the canopy of small woody plants can be accurately measured with a plumbline held against the edge of the canopy and vertically above the tape. The linear extent of the canopy of plants whose canopy is out of reach of the worker can be measured using the Andresen and McCormick (1962) "stick method". The worker first stands astride the tape and notes the point on the edge of the canopy vertically above the tape. Keeping an eye on this point, the observer then moves to one side of the tape until the vertical plane running through the point and his or her eyes is at right angles to the tape. The observer raises a straight stick to the point on the canopy and brings it down in a vertical plane to touch the tape. This point is vertically beneath the noted point. The moosehorn or map-tube method can also be used to look vertically upwards from a position astride the tape, and a plumbline attached to the base of the tube used to point to the tape.

The line intercept is of limited use for ecological monitoring in the Sahel, and its function is often - but not always - advantageously replaced by the more rapid and less laborious step-count method.

5.4 Nearest neighbour

In the nearest-neighbour method a plant is chosen at random (the usual technique is to chose the closest tree to a point selected at random) and the distance between it and its nearest neighbour measured. This measure gives an estimate of density.

Several variants of the method are discussed in Mueller-Dombois and Ellenberg (1974) and tested in Cottam and Curtis (1956). This method and its variants suffer from an acute dose of the same drawbacks as the PCQ (mainly that sahelian plant species are not distributed at random), and are not recommended. Since the method is currently relatively little used, it is best ignored.

5.5 Point quadrat (point centre quadrat, or PCQ)

The Point Centre Quadrat (PCQ) method consists of measuring the distance from a point chosen at random to the nearest tree of the given species in each of the four quadrats about the point. This measurement is repeated a number of times and the mean minimum distance used to calculate the mean density of that species.

The PCQ has been widely used by ecologists, despite cautionary advice from many authorities (eg Greig-Smith 1964, Risser and Zedler 1968, Mueller-Dombois and Ellenberg 1974 and many others), as a quick way of estimating the density, relative frequency and species composition of woody plants.

The main reason for not using the PCQ is that the formula (Appendix 2) used to calculate the mean density is based on the Poisson distribution. If the assumptions of the formula are to be respected, the plants should therefore be distributed at random with a uniform density. This is plainly not true in the sandy Sahel, where, for example, woody plants are strongly clumped in the interdune hollows and in microdepressions on the dune slopes. In Part II of this document the PCQ is examined in detail.

A variant of the PCQ, called the "wandering quarter" method by Catana (1963) is even more sensitive to the clumping of the sampled species, and requires correction factors which would normally make the PCQ preferable. The PCQ itself is easy to use, gives numbers which look deceptively like genuine data, and should be dropped from the repertoire of rangeland ecologists in the Sahel.

5.6 Plots

Plot sampling involves the evaluation of the parameter(s) of interest for every individual of a given species in a given area. Plots are generally treated as belonging to one of two types:

5.6.1 Quadrats

Despite its name, the quadrat may be of any shape, and is commonly circular, square or rectangular. Circular quadrats reduce the number of decisions to be made at the edge of the plot about whether an individual should or should not be included in the sample (most investigators tend to bias results by including more than they should). They can also be laid out from a single central point using a cord or wire of the correct length, which may be particularly convenient in measurements of woody species. Both circular and square plots may be generally less useful to an ecological monitoring unit than rectangular ones because they tend not to sample the variation in the vegetation that is possible with the rectangular quadrat. Where this is true they will tend to exhibit high inter-sample variance and a very large number of square or circular plots may be required to reduce the interval of confidence about the mean to a sufficiently low value for the requirements of the monitoring unit.

The size of the quadrat depends on (1) the purpose for which the data are being gathered, and hence the precision and accuracy required for the result, (2) the time and manpower available, (3) the need to reduce as far as practical the variance between samples, (4) the characteristics of the vegetation, especially the inherent variablility in the parameter(s) of interest, and (5) the desirability of reducing edge effects (given that the larger the area the smaller in proportion becomes the influence of decisions on the inclusion or exclusion of individuals on the boundary). It is therefore impossible to recommend a realistic quadrat size suitable for all needs, and it is not reasonable to expect that all the data used by an ecological monitoring unit will be collected from quadrats of a single size.

It is essential that clear guidelines are given to observers to enable them to determine whether or not a plant is inside or outside the sample plot. For single-stemmed annual grasses this is normally easily determined, but multi stemmed woody plants and some grass-layer dicotyledons may present problems.

5.6.1.1 Visual estimates

Within a marked sample area a trained observer may estimate cover, mean sward height, numerical dominance, greenness, biomass, and other parameters. Woody plant canopy cover, often out of reach of the observer, is normally best estimated by recording presence or absence of cover above selected points in the plot. Visual estimates of cover are likely to be inaccurate, although the visual estimate improves as observers train in the field (Smith 1944).

Field training is easily accomplished. The preferred technique is for the observer to make visual estimates of the parameters to be measured at a sample plot, then to clip, count, take radiometer readings or other observations as appropriate. The observer should compare the measured values with the estimated ones and try to adjust his or her mental set accordingly.

A large number of useful samples may be collected by calibrating visual estimates with objective measurements at a few plots. Sufficient coupled estimates are made through each day of data collection for a correction factor to be applied to the estimates made at plots at which more detailed measurements were not taken. Preferably, calibration should not be confused with training, and ideally, although normally this is not realistic, the observer will not be told the true values of parameters at calibration sites.

If two or more observers are available to make visual estimates, calibration can be carried out at shared plots. It is important under these circumstances that each observer write down their estimates, and preferably that they do not compare notes, so that the results at the calibration station are not influenced by majority opinion or that of a forceful or esteemed personality (neither democracy, autocracy nor gerontocracy have a place in ecological monitoring). Each observer will probably have his or her biases, which will flourish when they are collecting visual estimations on their own, and which can be corrected only if their opinion at the calibration plot was not influenced by others.

5.6.1.2 Charting: Cartesian, Analogue and Digital

For some monitoring (but not inventory) purposes it may be appropriate to chart the positions of plants in small sample plots. Woody plants are best charted by subdividing the quadrat or transect into manageable blocks, using pegs and cords, and measuring the x and y coordinates of the plants in the block. For very abundant plants, such as Boscia senegalensis in some areas, it may prove to be too labour-intensive to chart all the individuals, and the number of individuals in the blocks, or perhaps in sub-blocks, may be quite adequate for the purposes of the survey. The usefulness of this technique for monitoring depends very largely on the accuracy with which the pegs and cords are laid out at each visit. Wrongly placed markers will lead to woody plants wandering over the chart, which problem may or may not be resolvable in the analysis of results.

Grass-layer plants in the Sahel are generally not tall, and it is usually possible to lay a counting frame (Mueller-Dombois and Ellenberg 1974:82) over the plot. In some habitats it may prove difficult to lower the frame through the vegetation. In this case a device can be built consisting of a rectangular wooden frame, made up of two interlocking parts, each of which holds long wire pins which slot into holes drilled in the other half of the frame. The pins are arranged so that when the frame is assembled the pins cross at right angles and define small sub-squares. The two parts of this frame are then slid into place from opposite sides of the plot. Since the sides of the frame will sweep across the vegetation and bend the stems of plants rooted outside into the frame, the device is constructed so that the plot is defined not by the frame but by the first pin on each side.

All such devices are of little use if a woody plant happens to be rooted in a plot intended for sampling parameters of grass-layer plants. In this case it will be necessary to lay out the plot with rods or cords. A frame with three sides and a loose rod, or a circular wire frame with an arc missing may be useful, but there is no really satisfactory way of coping with such a circumstance except by defining the location of sample plots necessarily to exclude woody plants. This is probably undesirable, since livestock do, after all, graze near the stems of woody plants.

An analogue charting method which is of little general utility in monitoring vegetation in the Sahel, but which may prove useful for specific purposes, perhaps connected with soil monitoring, is the mechanical pantograph (Ellison 1942).

A field digitizer has been developed (Mack and Pyke 1979) which depends on a sonic emitter and directional microphones for data capture and a portable computer for recording and analysing the signals. This device can be used to record the position of individual plants in a plot which is small enough that the sonic signal is not attenuated by other vegetation. It has apparently never been tested in the Sahel.

5.6.2 Strip Transects

A strip transect is in effect a long thin rectangular quadrat. Inter-sample variance is reduced by orienting the strip so as to cut across any banding in the vegetation rather than to run parallel to it. The dimensions of the transect depend largely on the considerations listed in section 5.6.1.

In a heterogeneous zone such as the Sahel, where the woody plants tend to clump, samples based on circular or square quadrats may fall in a dense thicket or in an open space, and may therefore give results which are far from the true mean for the area. The standard deviation is therefore high and the confidence limits far apart; in other words, the measure is not precise. At least in theory the strip transect suffers less from the clumping of the woody plants, since it tends to cross many different habitats and thus gives rise to a composite mean, whose standard deviation is frequently lower than that of square or circular quadrats.

5.7 Other methods

The choice of method is largely influenced by the objectives of a given study and the range of vegetation types in which the method is to be applied. The variety of both aims and habitats means that no one method can be recommended as most appropriate for either inventory or ecological monitoring.

Apart from the more common methods listed above, there are many other methods sometimes used for the inventory and monitoring of vegetation. Useful reviews are given in Grieg-Smith (1964), Mueller-Dombois and Ellenberg (1974), Schemnitz (1980) and others.

6 Design of sample station

The sample station itself must be designed for the needs of the unit, and its design will probably change as the project progresses and learns from previous collection of data. Nevertheless it is as well to try to start with a good design which is itself statistically sound and which can be adapted easily. Since no single design can answer to all purposes, it is not possible to give in this document more than suggestions which may form the basis of a design adapted to the specific needs of the unit.

6.1 Conflicting needs of statistics and economy

As with the problem of location of stations, the demands of statistical soundness tend to lead to a large number of samples distributed in a relatively complicated way over the station. Repeatibility, economy, and the need to use a design which will not lead to unsupervised workers in the field taking "shortcuts" all militate for a simple design with few samples.

This conflict cannot be satisfactorily resolved, and the needs of practical ecological monitoring will probably mean that sacrifices are made to statistical soundness. While this is discouraged, it is realised that in the Sahel, ecological monitoring is carried out by sweaty, dusty and dazzled workers in the hot sun, who will not be able to bathe for as long as they are in the field, and that these conditions do not inspire great enthusiasm for fidelity to statistical purity. Realistically, then, it is the duty of the statistician to design a system which is as easy as possible to use in the field and as statistically sound as is reasonable. Too much emphasis on statistically reliable results will certainly lead to skimping in the field and hence to statistically reliable nonsense.

6.2 Methods used by the project

For the monitoring of grass layer species and the calibration of NOAA AVHRR satellite images the Pilot Project for the Inventory and Monitoring of Sahelian Pastoral Ecosystems used an extremely simple and rapid method designed to gather samples from as wide an area of its test zone as possible.

The test zone is crisscrossed by a network of firebreaks used mainly for communication. These firebreaks were used as the basis of the sampling design. The project sent two independent but cooperating teams into the field, each of which had to cover a different part of the field area. Every ten kilometers along the firebreak the team stopped and chose a site, about 100m from the firebreak, which seemed representative of the vegetation growth in the previous one or two kilometers.

At each station from 5 to 13 plots of one square metre were used to estimate the mean values of various parameters of the grass layer at the station. These parameters included the identity of the two dominant species (those species with the greatest cover), the reflectivity in certain bands of the electromagnetic spectrum, the visually estimated percent cover and the mean height of the stand, its clipped wet weight and its dry weight. The plots were located by selecting areas which, according to the most experienced member of each team, seemed representative of the station.

Woody plant species were inventoried in three studies, two along the crest of dunes. This habitat was selected because it seems from the literature that woody plant cover is changing fastest in areas of high, well-drained ground such as dune crests and slopes. This generalisation was certainly true at the site of the other study, a 25ha block containing dune crests, slopes and troughs (GEMS 1986e), chosen because the same block had been inventoried by other workers on previous occasions.

The dune-crest sites were roughly 50km long, one oriented roughly NE-SW and the other N-S. Stations were located every 2km along the crests. Each station consisted of a single sample of one hectare within which all woody plants were counted and their heights measured and health judged. On one dune the stations were permanently marked; on the other they were not. Some data were also collected by the PCQ method at these stations.

The 25ha site comprised a single sample in which every individual of all the woody species was counted and measured and in which the location of each individual of all but the single most common species was mapped.

6.2.1 Critique of project's sampling design

The project gathered a large number of samples scattered more or less at random throughout the area with the principal aim of calibrating AVHRR images from the NOAA satellites. Because of the dependence of the sampling pattern on the network of firebreaks, samples were more densely spaced in the western sandy zone than they were elsewhere (GEMS 1986d).

This distribution of sampling points, being unstratified, was somewhat inefficient. An attempt was made to stratify the samples by major soil type during analysis but this resulted in an irregular coverage of the various strata. Although the samples were regularly spaced along the firebreaks, the distribution of the stations was assumed to be random relative to the various levels of the Normalised Difference Vegetation Index (NDVI) calculated from the satellite data. Since no measure of the variability of the ground samples was used in calibrating the images (only the median value was used) this assumption is probably harmless.

The selection procedure of sites for stations cannot be considered to be unbiassed, since both they and the sample placements themselves were chosen to represent the average conditions in the neighbourhood. The effect that this bias had on the results is not known, but it is notorious that different researchers get consistently different mean biomass results in the area (A.Gaston and J.Valenza pers. comm.). A more objective method for the choice of site would be desirable. Except in the more densely wooded parts of the zone, it would have been preferable for sites not to have been always selected near to firebreaks, since the effect of firebreaks on nearby vegetation is not known.

Given the inherent variability of biomass production within the area of a single station, more than 5 samples per station should have been collected, and the number should have been standardized across all stations and years to allow comparison between sites.

Finally, at least some of the samples should have been collected at fixed stations year after year. This would have made all of the data, but especially those on species dominance, far more useful.

The work on woody species showed that that annual changes in numbers could not be estimated from the results collected on the dune on which there were no fixed sample points. Statistical problems might have been encountered had the data been analysed more fully, since the stations were located regularly, roughly every two kilometers along the dune crests. However, the location of each of the stations was otherwise entirely independent of that of any other station.

6.3 Sampling designs used elsewhere

6.3.1 LAT-Ferlo: the "Four Trees" method

A major project (LAT-Ferlo) working in the same field area developed a sampling design intended to provide information on the influence of the boreholes on the pastures and woody plants (Boudet 1980). The area was stratified by pasture type and all samples near a given borehole were collected in the same pasture type. Three stations were sited on a radius from the borehole, the first between 2 and 3 kilometers from the troughs, the second at about 5km and the third at about 9km. Each station was defined by four trees. A cord was drawn tight around the trees to form an irregular quadrilateral. Two more cords marked the diagonals and hence the centre of the station. A further two cords passed through the centre of the station, one parallel with the contour and the other running down the line of steepest slope.

The cords marking the perimiter and the diagonals were used as line intercepts, or rather, as very narrow (20m x 2cm) strip transects, for classing the abundance of vegetation growth (none, poor and well-developed) and the last two cords defined similar narrow transects for the collection of data on species composition and cover. The latter cords also marked two sides of a square of variable area which was clipped and weighed. The area cut depended on the biomass; clipping continued until 1.5kg had been collected, and the area clipped was then measured. This area varied typically between 10 and 25 sq m.

All woody plants in the circular hectare centred on the crossed cords (ie all those within 56.4m) were then inventoried.

6.3.2 Critique of the LAT-Ferlo sampling design

This method has the advantage that fixed plots were used, and hence results could be compared from year to year. By stipulating that all stations fell in the same pasture type, there was some assurance that measurable differences between stations were due to between-station variability and not to the "random" variability of the parameter being measured. More stations at each distance would have added to this assurance.

Unfortunately by defining the station by four trees at the corners, and by defining the transects to end at these trees the LAT-Ferlo team biassed their results in three major ways.

Firstly, the herbaceous layer in the Ferlo grows noticeably better under the canopy of woody plants. This effect is especially marked in years of generally poor production, which is to say, in the last decade. By starting and ending each transect under a tree the results were unduly influenced by these beneficial effects of the woody plant canopy.

Secondly, radiating transect lines over-sample the area near the point from which they radiate. Thus the arrangement of transects means that species near the centre of the plot are over-sampled.

Thirdly, the count of woody species centred on the crossed cords was inevitably biassed by the selection of four major trees to define where the cords crossed.

The "line intercept" method that they used, in fact a narrow strip transect, suffered from two failings: firstly, its length and hence its precision varied in an unknown manner from station to station; and secondly, its width was defined by the "width of a thumb" on either side of the line. This creates two problems - the most obvious being in the variability in thumbs - and the second in the inevitable difficulties of deciding on exactly where the boundary of a sample area is, the so-called "boundary effect". Long thin plots have more boundary, and hence more decisions, than do square or circular ones of identical area.

The technique of cutting until a certain weight of grass-layer biomass is reached means that errors arising from the weighing of very light samples are eliminated. The less the biomass the larger the plot, so that an accurate measure of biomass at the sample site is obtained. At first sight this technique seems reasonable.

Unfortunately as it stands the technique is flawed, as can be shown by a simple "thought experiment". If by chance the cords define the edges of a small area of high productivity in the midst of a relative desert, clipping will stop before the edges of the oasis are reached. If on the other hand the cords define the edges of a square patch of naked soil, surrounded by good growth, the clipping will be concentrated on the border of the sterile area, and again a false idea of the mean production will be obtained. In general, areas of low production are oversampled and areas of high production cause the clipping to halt. In other words, by cutting a single square of variable size the LAT-Ferlo team did not sample the mean production of the station.

6.3.3 The Boudet variation

In 1980 the LAT-Ferlo design for the collection of data on grass-layer production was modified (Boudet 1983). Six transect lines were laid out parallel with the cord placed along the contour. On each line 5 one-meter square sample sites were arranged at random, and biomass was measured by clipping at each of these sample sites. This method is less subject to bias than was the earlier one, and with 30 samples per station the mean biomass could be adequately estimated. The residual bias concerns the use of four major woody plants to define the stations.

6.3.4 The "Botswana Star" method

Field (1977) and Field and Glatzle (1978) describe the sampling design used by a monitoring unit in Botswana, in which stations are chosen by stratification and the use of aerial photographs and range maps. Each station consists of a central point from which three transect lines radiate. The angle between the lines is 120 degrees, and one is aligned north-south in flat areas or along the line of greatest slope. Each line is 50m long. At the far end of each line are two 10 x 20 meter plots arranged so that each plot has a 10m side contiguous with the transect line and so that the two plots share one of the 20m sides. The plots lie to the right of the transect lines to the observer facing them from the centre of the "star".

Each 50m line is treated as two 25m line intercepts for the measurement of cover. At 5m intervals on each line intercept is a 30 x 30 cm plot which is clipped for the measurement of biomass production.

6.3.5 Critique of the Botswana Star sampling design

In this case, because the perennial grasses in the region typically grow in tussocks, the line intercepts can be true lines. Sparse annual grasses, with their single stems, cannot reasonably be inventoried with this technique, which in most years would systematically give results in the region of 95 to 99% naked soil.

The combined elements of the Botswana Star design ensure that the samples are sited in a regular pattern, and that they are therefore not independent of one another. This gives rise to technical problems with the statistical analysis of the data. Once again, as with the Four Trees method, the radiating arrangement of sample lines results in an over-sampling of the habitat near the centre of the star relative to those at its outer limits.

This design has been severely criticised by Prince (1982), especially for its complexity and substantial workload which leads the field workers to spend too little time at each station for them to be able to collect the data honestly. Unfortunately, Prince's suggestions for remedying the problems, while statistically impeccable, would seem to involve even greater complexity and yet more work.

6.4 Proposal for a design for calibrating NOAA images in the Sahel

In the Sahel, since the economy of the area is largely pastoral, the principal concern of most ecological monitoring projects is the pastoral ecosystem. An extremely useful tool in monitoring pastoral primary production is the Advanced Very High Resolution Radiometer carried on board the National Oceanographic and Atmospheric Administration satellites. The data from this instrument can be used to derive various indices which can be related to plant growth. One index of particular interest is the Normalized Difference Vegetation Index (NDVI) (see GEMS 1986d and section 7.2.5.4.3).

The design presented here is intended to be used specifically in the initial attempt to calibrate the NDVI so that the index can be used directly as a measure of standing crop at the end of the rainy season. It is therefore concerned with measuring grass-layer production in a short period at the end of the growing season, and is not directly applicable to the measurement of growth through the season. It assumes that the unit has access to only two vehicles and four fieldworkers, and if more vehicles and workers are available, the sampling density can be increased accordingly or further strata can be sampled.

For this purpose grass-layer vegetation monitoring stations can be concentrated in the zones of greatest importance to the pastoral economy. In most of the Sahel this is the sandy zone, and in the initial design, the whole of the sandy zone is taken to be sufficiently homogeneous to be treated as a single stratum. Experience will show in how far this is justified. All the sampling effort is concentrated in this zone, so that at best, the NDVI will only be correctly calibrated for the sandy zone. Any additional workforce should probably sample in the gravelly zone rather than be used to extend the sampling network in the sandy zone.

In the Sahel rainfall and hence productivity diminishes from south to north (see GEMS 1986b for a description of the rainfall in the Ferlo, for example). Thus in order to sample a wide range of production the sampling effort should be aligned generally north-south. With two teams this implies two roughly parallel lines - which for reasons of accessibility will probably not be exactly rectilinear. Each line contains five transects, which are oriented east-west in order to reduce the internal variability of the transects. The transects are roughly equally spaced (Figure 3), but are carefully arranged so that they do not cause plots to fall in highly disturbed areas, such as the vicinity of a borehole.

As will be seen, the regular spacing of the transects does not imply that the sample sites are interdependent.

Each transect is 1500m (1.5km) long and is made up of 10 stations (Figure 4), each 100m x 150m (Figure 5). In the office a table of random numbers is used to select, for each station, the location at which a single steel tube will be deeply embedded. The tube must be clearly visible, and if it is placed inside a bush measures must be taken so that it can be found on subsequent occasions.

Each steel tube marks the corner of a small series of sample sites. The number of sites depends on the needs of the monitoring unit and the variability of the parameters to be measured, as explained in section 2.2.1.3, but there should probably be no fewer than 8. Each site should be no smaller than 1 sq metre, and the plot should preferably be circular. Stout reinforcing wire can be used to make suitable circular frames.

The sites are arranged in two parallel lines far enough apart so that each worker can collect data undisturbed by the movements of the other. The two lines are close enough for an exchange of views and judgements where necessary. The plots are spaced so that their nearest points are at least 2 and at most 5m apart, the placement on each of the two lines being different, and predetermined from a table of random numbers in the office (Figure 6). The placement of circular wire plots in the field is made easier if each worker has a cord knotted at the appropriate places and long enough to show the location of all of the sites on his or her sample line.

A complete set of schematic maps of the sampling lines, transects and plots should be kept in the office and copies given to each member of the teams before leaving the office for the field. This map should show accurate distance measurements so that if markers are uprooted their location can be determined and a replacement post installed.

This system allows sample points to be found rapidly, diverts more time to sampling than to driving between stations, and is statistically sound. Although only ten points on the AVHRR image are sampled, these points are arranged so as to cut across as many biomass classes as possible, with the intention of using the profile thus developed to calibrate the images by regression of clipped biomass against the NDV Index.

6.4.1 Use of design in the seasonal monitoring of grass-layer plants

With minor modifications the design can be used for the placement of plots for the monitoring of grass-layer plants through the year, bearing in mind that any destructive sampling can only be done once per year per sample plot.

Figure 3: Schematic arrangement of five transects on each of two lines

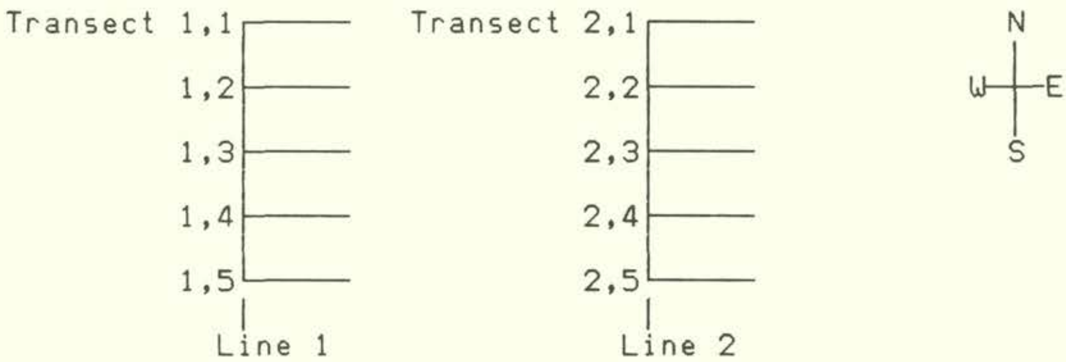


Figure 4: Schematic arrangement of stations on the transects

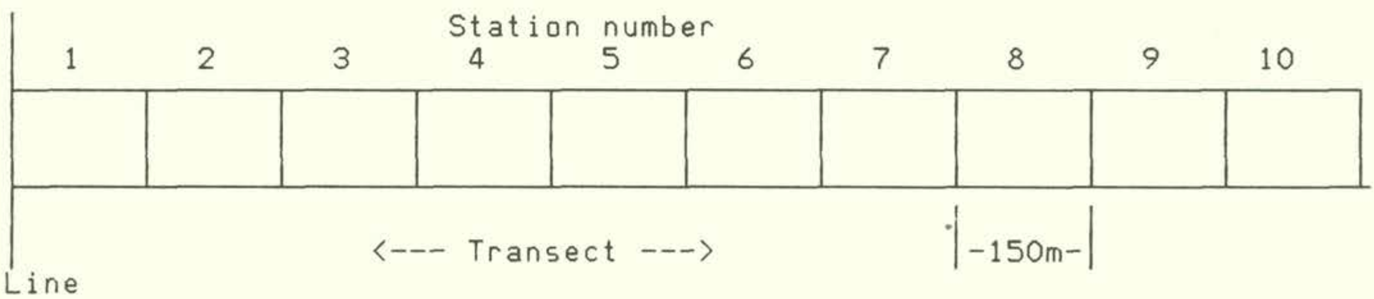
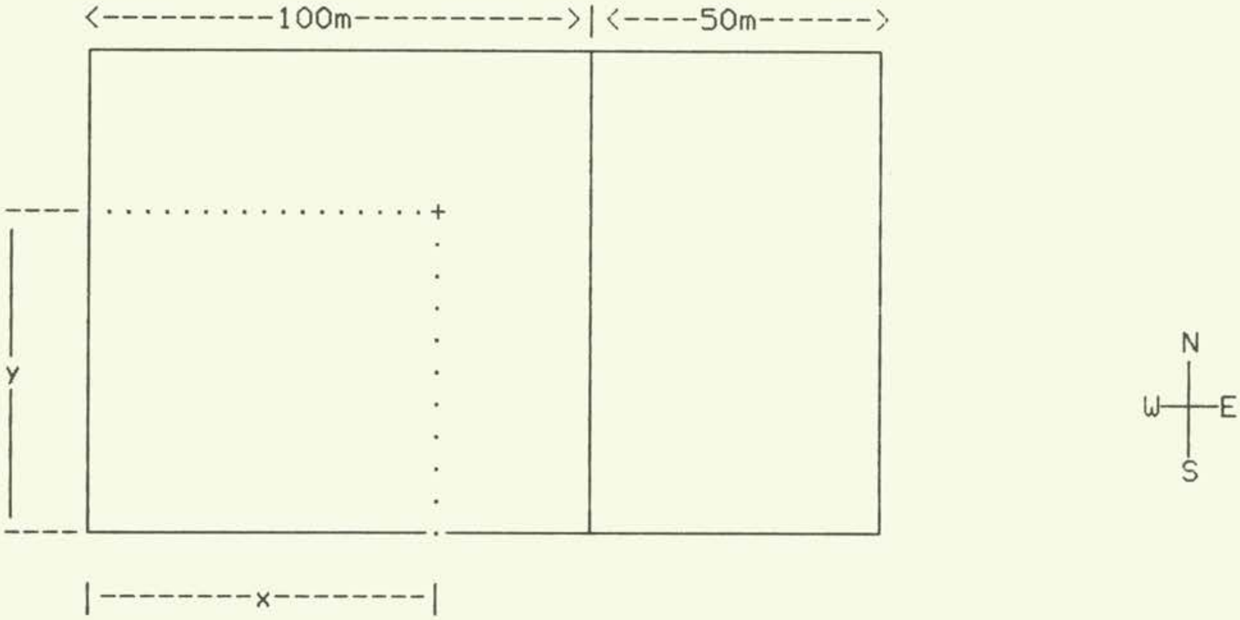
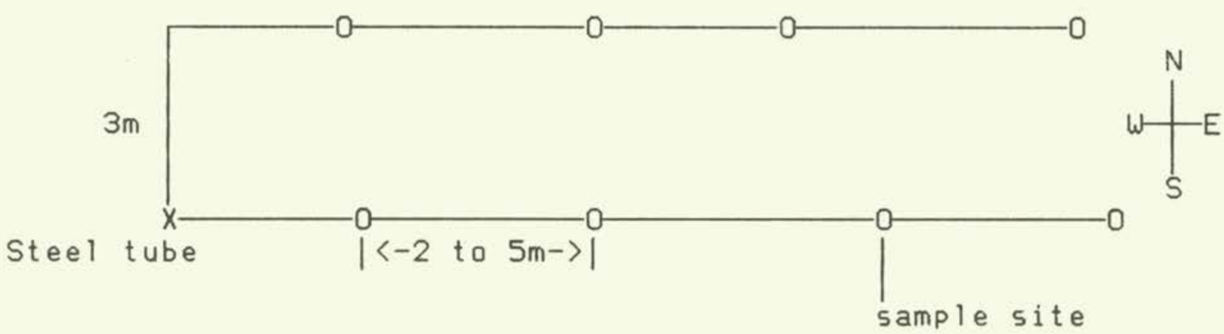


Figure 5: Location of steel tube within the station



At each station the distances x and y are chosen from a table of random numbers such that both x and y are less than 100. A 50m gap seperates stations so that if x is close to 100 the sample sites will not overflow into the next station.

Figure 6: Schematic arrangement of sample plots at each station



6.4.2 Use of design in the inventory of woody plants

Since there are fewer time pressures in monitoring of woody plants, this system is probably unduly restricted for most needs, given that in the Sahel a team of three people can inventory the woody plants of roughly 6 hectares in a day.

For reasons of efficiency and economy the stations in the design outlined above, identified as they are with permanent markers, may form part of the network used in yearly monitoring of changes in woody plant cover. Knowledge of woody plant growth in the vicinity of grass-layer sample sites is probably also of interest.

If it is not intended to use the samples for making generalisations about the surrounding woody plant vegetation, the plots can be regularly spaced along the transects. A possible distribution is shown in Figure 7. By locating the centres of the plots at random within limits (in a predetermined and recorded way which remains identical from year to year) around these points, the statistical problems associated with regular spacing are reduced and the samples can be treated as representative of the transect as a whole.

With the minimal design outlined above and with 6 woody-plant stations on each transect there are 60 stations in the zone . It may prove necessary to mark the centre of each circular plot with a steel tube or other permanent marker.

7 Parameters to be sampled

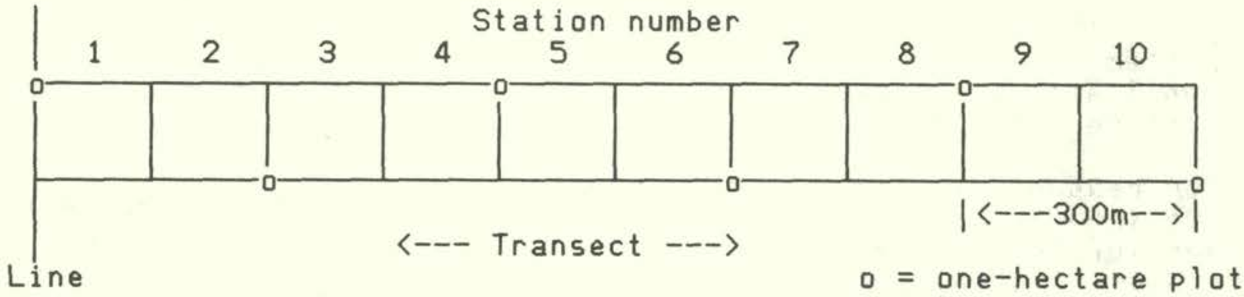
This section of the document contains suggestions on which parameters may usefully be monitored in a typical pastoral monitoring project in the Sahel. The needs of inventory are not specifically addressed. It is not possible in a general document to give firm guidelines to the parameters that should be collected, or the detail required in any given programme, since the adequacy of the data depend on the objectives of the unit.

The most urgent task of many monitoring units is to serve as an early warning system of environmental degradation (indeed "monitor" comes from the Latin "monere", "to warn"). Some of the parameters considered here are therefore designed to be indices of degradation easily detected in the field. Noticeably missing are the parameters frequently monitored in industrial or agricultural areas with the intention of detecting or measuring pollution (eg Bernes et al 1986).

7.1 Soils

Although this document is chiefly concerned with vegetation sampling, the status and trend of soils can often usefully be monitored at the same time as the vegetation. While they are of basic importance to the ecology of the pastures, and must not be ignored by a unit wishing to evaluate condition, the soils are frequently overlooked, especially by zoologically-oriented ecologists. In part, this is due to the daunting complexity of a full assessment of soil degradation (see for example FAO/UNEP/UNESCO 1979). However, the most animal-minded ecologist in the

Figure 7: Layout of plots for monitoring woody plants along the transects used for the grass-layer sampling.



This arrangement gives 6 hectares per transect, which can be inventoried by a single team in a day in most sahelian habitats.

Sahel will have noticed that it is difficult to walk in the deep loose sand, filled with burrs, and black with dried and powdered dung, that surrounds each borehole for several tens or even hundreds of metres in the dry season. Following the herds through the bush he or she will have seen the wide areas of hard sterile earth, and will have found that these patches consist of a crust of fine packed sand overlying a deep layer of grainy quartz particles. Palls of atmospheric dust turning the sky into a bright white or dim yellow bowl for weeks on end, and scudding snakes of blowing sand coiling across the landscape force themselves on the attention of any observer. At least some of the evidence of degradation of the soil is not hard to see.

7.1.1 Indices of soil degradation

To most units monitoring the ecology of a pastoral ecosystem, the more detailed aspects of soil assessment are largely unnecessary, and approximate, even qualitative, measures are adequate. The range manager needs practical measures that are simple and can be easily collected. A list of such measures is given in annexe to the FAO/UNEP/UNESCO (1979) report, but many indices in the list are of limited use in the Sahel. An adapted list is given in Appendix 3 to this report.

7.2 Plants

Vegetation descriptions are probably the most important information obtained from range inventories. The condition of the vegetation tends to change rapidly in response to use by humans or their livestock, while the condition of the livestock itself changes much more slowly, often only after its environment has been seriously degraded.

Experience in the rangelands of the United States has shown that there is a tendency for inventory and monitoring teams indiscriminately to measure every attribute of vegetation (Smith 1984), much of the resulting data remaining unanalysed, unused, and therefore useless. The objectives of the ecological monitoring unit, constrained by time and manpower, oblige it to chose from among the wide range of data which could be usefully collected for ecological monitoring purposes, including:

7.2.1 Species composition

Species composition is derived from measures of relative frequency, relative density, or relative cover. These three measures do not in general give the same results and hence the method used to derive the species composition must be stated explicitely. The most frequent measure is probably density but cover normally has greater ecological significance.

The reliability of species identification is improved by giving each observer a manual containing colour photographs or life-sized drawings of plants or plant parts of all the species he or she is likely to encounter. For woody plants see, for example, Weber et al (1977). An alternative and highly useful field-guide for the Sahel, especially for the grasses, is constructed from a looseleaf binder containing commercially available plastic sleeves opening from the top. Blank sheets of absorbent paper are inserted into the sleeves to provide a background to the one or more plants or plant parts that are slid into the sleeves on both sides of the paper. A typed or hand-printed label is included with each specimen (Figure 8). If kept in a cool dry place between seasons, this herbarium can be built up over one growing season and used in the field on subsequent occasions. Each herbarium should be checked by the senior plant ecologist before each field season.

7.2.2 Plant frequency

Frequency, which depends only on presence or absence of a species in a sample, is a quantitative measure which is more rapidly made than estimates of density or cover, especially in species-poor habitats.

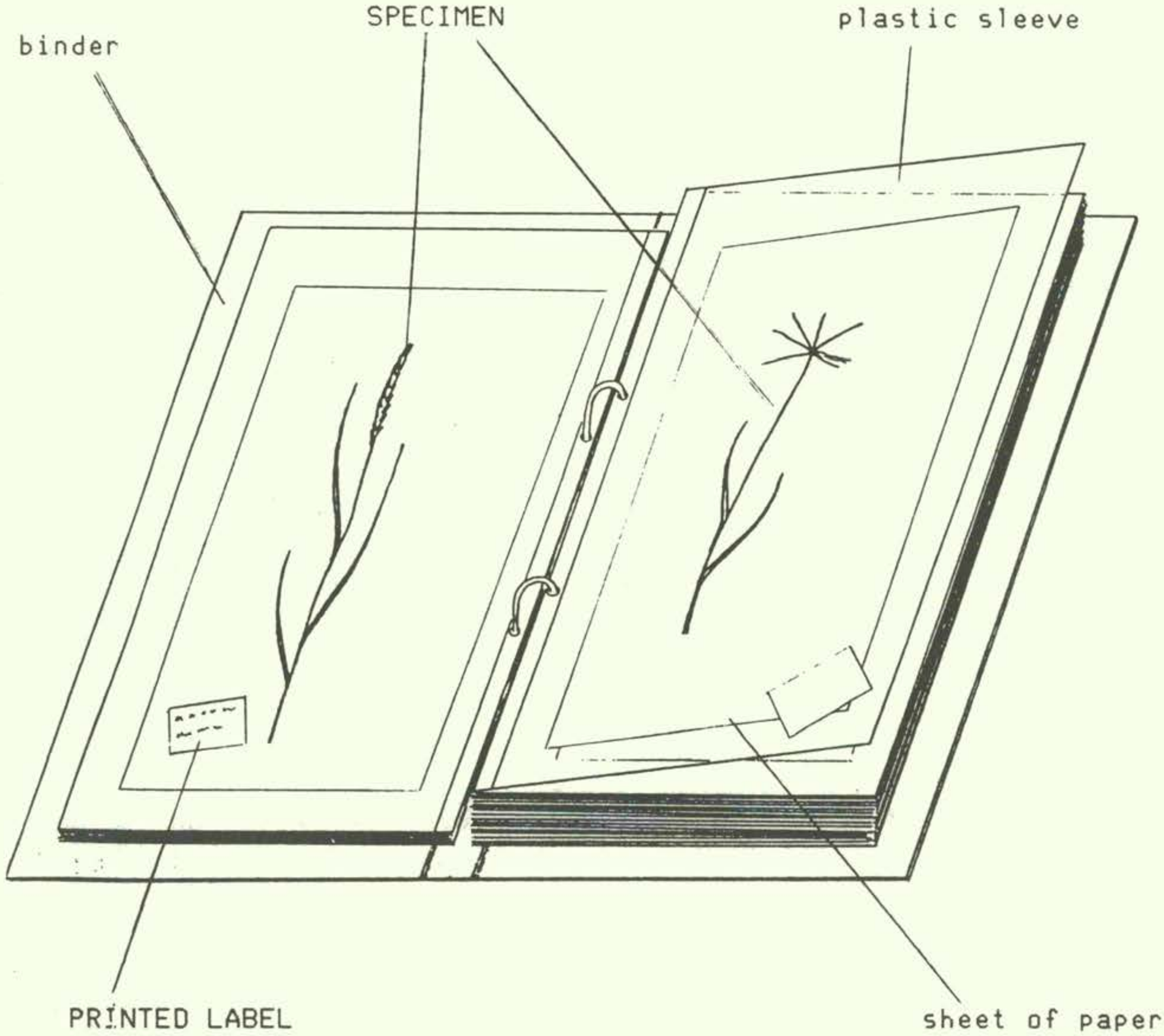
Repeated frequency scores may indicate the invasion of some species and the disappearance of others. Frequency can therefore be a useful measure in a monitoring programme. Frequency is generally less useful for inventories, partly because by itself it means little, and even the relative frequency of various species is only useful in the unlikely event that the several species have a similar growth form and distribution pattern.

It should be stressed that comparison of frequency between habitats or with other studies in the literature is only possible if the size and shape of the sample plots is identical, and even then frequency may give misleading results if the distribution pattern of the species changes between sample sites or dates. Frequency determined by plotless methods - such as the PCQ - is a hybrid measure of the relative density and dispersion of the species. The "frequency" arrived at by the PCQ, for example, is the answer to the implicit question "what is the probability that the plant nearest to a point chosen at random in this habitat belongs to species x?". It is hard to imagine the ecological usefulness of such a measure, except inasmuch as the "species composition" derived from PCQ measurements may conform to the observer's subjective view, since his or her impressions of species composition will depend on just such a probability. This is unlikely to make the measure useful in deciding on areas to be designated recreational areas of particular interest, or ordering descriptive entries in a Park handbook, since subjective impressions are more rapidly gathered than are PCQ measures.

In general, the frequency with which a species is observed in samples is strongly influenced not only by the density and cover of the species, but especially by the pattern in which individuals of the species are typically found. In the Sahel, where individuals of most plant species generally grow in clumps, the influence of pattern on frequency is particularly noticeable.

In a random distribution the presence of one individual does not influence the probability of finding another individual nearby. Where the distribution of individuals is random, density may be obtained theoretically from frequency. Random distributions of plant species are rare (unknown?) in the Sahel, and it is unlikely that a close relation exists between frequency and density for these species.

Figure 8: Looseleaf folder with plastic sleeves used as a field herbarium



Cover can never be inferred from frequency except in the special case of point samples, where the sample plot is reduced to a point, and frequency theoretically gives an unbiassed measure of cover. However, since the pin is ideally dimensionless, the diameter of the pin, relative to the typical dimension of the individuals being measured, affects the estimate of cover. If the pin is not sharp it is necessary to correct for its diameter if the estimate of cover is to be accurate (Warren-Wilson 1963).

The most useful plot size for frequency measures is one for which the most frequent species of interest does not quite reach 100%. Clearly this can only be determined after considerable field experience, and, given the annual variability in distribution and density of some species, perhaps only after several year's fieldwork. Early frequency measures may therefore be of little use for comparison with later results. It may be wise to start frequency measures with a "geometric series" plot in which a very large square plot is divided in half and one of the halves itself divided in half. The size of the half-plot is determined by initial trials in the field to fulfil the requirement in the first sentence of this paragraph.

7.2.3 Plant Number and Density

Perhaps the most intuitively obvious measure of a population of anything is its number. The natural way to relate number to area is to calculate density, which is therefore a measure that is easily understood. This is an important and useful attribute for the transmission of ideas and information. Density has the additional advantage that measures collected by different methods can usually be compared directly.

Despite the attractions of the measure, it has drawbacks. Firstly, density is usually of less ecological significance than is cover (Daubenmire 1968), since knowing that a plant is present at several hundred per hectare is not normally as useful as knowing that those hundreds perhaps only cover a few square centimetres. Secondly, the collection of estimates of density is usually time-consuming. Thirdly, in the inventory of rangelands it may prove to be necessary to collect a very large number of samples in order to obtain adequate precision for a statistical test - which may then turn out to be unable to detect differences in density that are quite obvious to the observer in the field (Gysel and Lyon 1980).

Thus although intuitively easy to understand, density has not proved to be particularly useful for rangeland inventory or monitoring (Risser 1984) except in determining species composition of an area (see section 7.2.1). Frequency is so much easier to collect than density that it may be preferable in a monitoring programme to collect frequency, although this will depend on the purpose of the inventory or monitoring since the information conveyed is not the same. On the other hand, density may be obtained as a by-product of some measures, as is the case with basal area or height, for which each individual in a plot or transect may have to be measured.

7.2.4 Cover and Top Cover

Cover is bound to be high on the list of priorities for any ecological monitoring programme. It is probably the best single vegetation parameter for monitoring the impact on the rangelands of natural or manmade changes in the environment.

Cover, like density, is a measure which is intuitively easy to grasp, and has the advantage that it is generally a useful ecological measure since (1) it gives information about the structure of the vegetation, (2) it is of direct ecological importance to the soils, other plants, livestock and human populations, (3) cover may be very sensitive to ecological change, and (4) the cover of most sahelian plants can be estimated if not measured. Since cover is highly variable from season to season, comparisons to detect trend in rangelands should only be made between samples collected at the same time of year, that is, in the same season.

Unfortunately cover is generally tedious to measure objectively, and visual estimates are frequently used. For visual estimates of the cover of grass layer plants in plots it may be useful to prepare cardboard squares of 1%, 2%, 5%, 10% and 20% of the area of the plot.

Inter-observer reliability is likely to be low, and as far as possible the same observer should make estimates from the same plots in any repeated sampling. If, before starting the sampling and if possible at intervals during the sampling, the various observers make independent estimates of the same set of plots, inter-observer correlation can be used to standardise their visual estimates.

It may be impractical and of little importance to measure cover to the nearest percent, and cover classes may then be used, with the advantage of increased precision to be weighed against the loss of accuracy. The six Daubenmire (1958) classes (0-5%, 5-25%, 25-50%, 50-75%, 75-95% and 95-100%) may be adopted for most purposes.

It is important to use methods which will correctly measure cover or top-cover as required, in those areas in which there are overlapping canopies.

7.2.5 Basal Area

The basal area of sahelian grass species is rarely more than 3-4%, and it may be difficult to devise a technique sufficiently sensitive to measure even relative large percentage changes in basal area. However, the measure is of considerable ecological significance, since basal area of plants in a region is likely to be inversely proportional to the susceptibility of the region to soil erosion.

Basal area of sahelian woody plant species is a useful parameter in inventories for the comparison of regions. However, it may be difficult to measure the basal area of multi-stemmed species, and for these species it will probably be worthwhile to calculate the mean stem basal area for individuals of a given height. If a clear relationship is found, number of stems and height of individuals may be used to estimate basal area for that species. Basal area of woody plants may be found to change significantly between surveys separated by a few years, and although less intuitively obvious than cover, this statistic may therefore be useful in education of target groups in the changing environment of the Sahel.

While in temperate woodlands and forests the "basal" area of woody plants is often measured at chest height or at 1.4m, or other specified distances a metre or more from the ground, in some parts of the Sahel this criterion would mean that most of the woody plant biomass would not be measured, since many woody plants are not as tall as this. Indeed, in the Sahel, basal area is often measured at a height of 10 or 20cm above the ground. Whether or not this criterion is adopted, the standard height at which basal area is measured must be mentioned in all reports concerning the parameter.

7.2.6 Biomass

Biomass, or weight, is not normally of interest in itself, but for its importance to livestock or as an indicator to the condition of the rangeland. Biomass should certainly not be the only basis for determining grazing capacity or stocking rates, although in practice it often is. Biomass is measured by four main groups of methods:

7.2.6.1 Visual estimates

Called "ocular" estimates by American range managers, the visual estimate of biomass depends at its simplest upon the observer to judge the weight of the individual plant or the weight per unit area of the sward. For some applications a sample (with woody plants, the sample is usually a twig) is clipped and weighed, and the observer then estimates the number of such samples (twigs) on the plant.

Visual estimates of biomass tend to be at least 5 to 10 times as fast as the clip and weigh method.

The method of visual estimation and its variants are discussed in detail in section 5.6.1.1. When estimating biomass, expert observers tend to bias their results towards what they know the habitat normally produces under prevailing conditions. That is, they tend to overestimate weights when biomass is exceptionally low and underestimate them in years of unusually good production. This bias can be corrected by the technique of double sampling and regression, as discussed in 5.6.1.1.

7.2.6.2 Correlations

Estimates of biomass can be obtained by knowledge of the equation of the major axis (Sokal and Rohlf 1969:526) of correlations between biomass and other parameters of the species concerned. Biomass has been shown to correlate (for a given species, habitat and year) with canopy cover (Payne 1974), the mean height of the stand (Heady 1957), the product of height and cover (GEMS 1986d), and the density of the species (Laycock 1965).

7.2.6.3 Clip and weigh

The most conceptually simple of all the methods of measuring biomass, clipping a plot and weighing the clippings is also tedious, time consuming and expensive. For obvious reasons, clipping is known as destructive measurement, and is only carried out more than once on the same plot in the same year for specific purposes. Destructive measurement of the woody plant layer is particularly difficult and expensive, and moreover often ecologically and politically undesireable.

As a result of the financial and labour costs of the method, it is likely that for at least some strata the ecological monitoring team will be unable to sample sufficient plots to get a representative or statistically sound estimate of the biomass in the stratum.

The heights reported in the literature at which the sward is clipped vary from study to study. In short grasses any stubble left above ground level will reperesent a significant proportion of the aboveground biomass. In years of poor production the grasses may not even reach the criterion height, and returns of zero biomass will then be given for areas that even if threadbare are far from denuded. It is therefore recommended that sahelian grasses are clipped at ground level.

Electric sheep shearers driven by a 12 volt car battery and connected to a vacuum collecting device can speed up the work and minimize errors caused by uneven clipping (Risser 1984). If biomass measures of seperate species are required this technique is not likely to be useful, since the species will get mixed up as they are clipped.

Unless livestock takeoff is accounted for, clipping and weighing must underestimate primary production. Without attempting to adjust for the different take-off rates in different seasons, and without taking into account seriously overgrazed pastures, one might guess that in the Sahel, where the growing season lasts for two or three months, something between one sixth and one quarter of the year's takeoff has occurred before the end-of-season clip takes place. If the aim of the unit is to estimate forage for the dry season, this is immaterial, but for other applications the growing season take-off must be considered.

7.2.6.4 Indirect methods

Three indirect methods of estimating green biomass of the grass layer may be useful. These are:

7.2.6.4.1 Beta attenuation (Teare et al. 1966)

The method depends on the degree to which moisture in vegetation absorbs fast-moving electrons (ß-particles) emitted from a radioactive source. The more green vegetation (which contains water in the cytoplasm) between an emitter and receiver, the fewer electrons arrive at the receiver. If emitter and receiver are kept at a fixed distance apart and lowered into the vegetation, the decrease in the rate at which electrons arrive at the receiver is proportional to the amount of moisture, and hence of vegetation, between the emitter and receiver. Theoretically the biomass of a homogeneous sward can therefore be estimated once the instrument has been calibrated for the species concerned.

This instrument is of limited use in the pasturelands of the Sahel, where the moisture content of grasses can vary from day to day, from hour to hour and place to place, depending on saturation vapour pressure, ambient temperature and radiation flux, and where homogeneous monospecific stands are the exception rather than the rule. Frequent calibrations, involving clipping and weighing, make this method more laborious than it would first appear.

7.2.6.4.2 Capacitance (reviewed in Neal and Neal 1973)

The capacitance meter measures the ratio of capacitance of a fixed air-gap with the same distance through the vegetation. Air has a low dielectric constant, while water has a high one. The presence of green vegetation between the plates of the meter thus alters the capacitance in proportion to its water content, and hence to its mass.

As for the method of beta attenuation, the capacitance meter is sensitive to changes in the water content of the vegetation, and it therefore suffers from the same drawbacks as the previous method.

7.2.6.4.3 Spectral reflectance (Pearson et al. 1976)

Actively photosynthesising chlorophyll molecules absorb light in several discrete bands of the spectrum, the most important of which (due to chlorophyll α) is at about 675nm (Rabinowitch 1958). The cell walls of plants reflect strongly in the near infra-red (between 750 and 1100nm), a feature that familiar to everyone who has seen false-colour infrared images of vegetation. An instrument capable of detecting these two wavebands (R at 675nm and IR at 800nm) is therefore capable of measuring reflectance proportional to the surface area of plant matter (in the infrared) and the reflectance inversely proportional to the activity of the chlorophyll in that plant matter (in the red). This is the principle of the radiometer method of estimating biomass.

This is an area of active research, and various indices derived from the measures of reflected radiation R in these two wavebands (R675 and R800) have been proposed and tested. The simplest is the ratio R800/R675 (Pearson et al. 1976), but this has largely been superseded by the index (R800-R675)/(R800+R675), called the Normalised Difference Vegetation Index (NDVI) by Tucker (1980). This index gives good results in sahelian rangelands, but care must be taken to calibrate the instrument correctly both for the conditions of incident light (a plate that reflects incident light equally at all wavelengths is frequently used for this calibration), for the vegetation type being measured, distinguishing particularly between mono- and di-cotyledon species (GEMS 1986c), and for the soil type and moisture content. Other indices are also worth investigating.

7.2.7 Seed production and seedling establishment

As a primary measure of the reproductive vigour of woody plants, fruit and seed production may clearly be of considerable interest to the ecological monitoring unit. Seedling establishment gives a clear indication of the future of the species in the area, and is often a more important parameter than seed production. The ratio between seed production and seedling establishment is a possible indicator of range condition, incorporating grazing pressure, soil and climatic suitability.

The fruits and seeds of small woody plants can be gathered within sample plots. Fallen fruit can also be collected. Tall woody plants present problems, and fruit traps are unlikely to be of use if they must be left unattended. Visual counts are possible for plants such as Balanites aegiptiaca, with large fruit visible through sparse foliage. Indirect methods may be feasible for some other species. Unfortunately, counts of fruit and seed production of woody species, despite their ecological interest, are labour intensive and should therefore not normally be undertaken without very good reason. Fruit production of grass species is likely to be of interest only for specialised studies, and the techniques needed for such work fall outside the scope of this document.

Seedling establishment should be monitored at fixed plots, preferably at the end of the rainy season when the initial establishment can be recorded, and again at the end of the dry season when survivors are counted. If the identity of the seedlings which have disappeared is of interest the location of seedlings should be recorded on charts of the sample plots.

7.2.8 Floristic species composition

Species composition is a sensitive indicator of ecological change, and in both inventory and monitoring the species composition of plots, and by extension, strata, will probably be estimated or measured. It may be sufficient to record percentage frequency, but relative densities, and to an even greater extent, relative cover, are generally more useful for the comparison of areas.

7.2.9 Structure and life forms

The life form of a plant may vary greatly over the range of the species, and in the initial inventory a description of life form may help in comparison of widely separated areas.

The structure of a woody plant gives a clue to its past history, exemplified by sculpting as a result of heavy browsing. To the experienced range manager the shape or structure of woody plants is therefore a powerful indicator of range use and condition.

Because the shape of the plant may reflect the intensity of browsing pressure, repeated census of charted plots in which plant structure is recorded will help to clarify the causal factors influencing the relationship between the size of the plant and its age.

7.2.10 Height of individuals and of stand

Height of grasses is among the more important measures for an ecolocical monitoring unit, since the height of grass-layer plants is frequently correlated with the biomass of the sward, and height is then an indirect measure of forage yield. For woody species the height of individuals is often assumed, and sometimes known, to be related to the age of the individual. Under intensive grazing pressure this relationship may not hold, and specialised long-term studies would be needed to establish the correlation under given ecological conditions. If it is not known - as is the case for most sahelian species - it is preferable when reporting results based on heights to leave units of measurement in terms of height rather than converted to age estimates.

Heights need not, and usually can not, be measured accurately, and height classes are normally used. For grasses, the mean sward height can normally be measured to the nearest 2cm. For smaller sahelian woody species a class width of 20cm is usually adequate. These classes are conveniently marked on a long stave in conspicuous colour (usually white) and the marks renewed as often as nescessary. It is not convenient to measure larger species in terms of 20cm blocks, because of difficulties of parallax. Although the analysis and interpretation of the data is usually made easier if class-widths are the same over the entire range of measurements, for most applications in vegetation monitoring it is not necessary to use a constant division of the height scale. A quasi-logarithmic stepped scale may be useful, in which the first five clases are 20cm wide, the next five are 40cm wide, and the next five are 80cm wide. Plants less than a meter tall are therefore measured to the nearest 20cm (precision of +/- 10% for the tallest plants), those less than 3m tall to the nearest 40cm (+/- 7%), and those between 3m and 7m to the nearest 80cm (+/- 6%).

7.2.11 Phenology and greenness

Measures of cover depend on the phenological state of the plants, and therefore all published estimates of cover should explicitely state the date or at least the season of the sample and the phenological state of the various species concerned.

The primary production of a sward can be estimated visually by an experienced observer by considering both the proportion of the ground covered by grass and its greenness (Lamprey and de Leeuw 1986). This parameter may be of limited use for estimating biomass of the grass layer in the Sahel, where annual species are very green as they grow rapidly during the short, unimodal rains, and are brown for the rest of the year.

7.2.12 Chemical composition, digestibility and palatability

The value of a pasture to livestock does not only depend on the biomass, but is determined largely by the nutritional qualities of the species in the pasture. It is usually not necessary for a monitoring unit to carry out its own examination of the chemical composition, digestibility and palatability of the various fodder plants in the zone, because these data are usually to be found in the specialised literature (eg Baumer 1983). In some cases lists of the fodder species can be found in which the plants are classed by some composite measure of pastoral value. One such list of grass-layer plants classified by pastoral value, extremely useful to any range manager in the western Sahel, is given in Boudet (1983) and reproduced in Le Houérou (1986).

7.2.13 Vigour and health

Vigour is probably high on the list of priorities for an ecological monitoring programme, given its sensitivity to range condition. Estimates of vigour and health, including signs of axe damage on woody plants, can be made at the same time as inventories of number, height and cover. Such estimates are best made in terms of a few classes, perhaps along the lines of:

Class A: healthy
Class B: some traces of disease or damage
Class C: noticeable mortality or several damaged branches
Class D: most of plant dead or mutilated
Class E: standing dead
Class F: fallen dead

7.2.14 Condition

A useful biological indicator of range condition in the Sahel is given by the species composition of the community of annual grasses. Overgrazed pastures are frequently dominated by the more opportunistic and less palatable grasses, including Aristida spp, Cteneum elegans, Eragrostis ciliaris, Sporobolus pectinellus and Tragus berteronianus.

A further biological indicator of range condition is given by the ratio of the abundance of seedlings and young woody plants to the abundance of adults of the same species. Although a high proportion of young individuals of some species - the so-called invaders - indicates degrading rangeland, the more usual clue to an unhealthy ecosystem is the absence of young individuals of many woody plant species in an area containing adults of those species. High adult mortality of woody plants may not be a sign of poor condition, since in the Sahel many populations of woody plants are made up of individuals of the same age, and massive local die-off may be a natural occurrence in the species.

Physical indicators of an unhealthy environment include signs of accelerated erosion and changes in the physical properties of the soils such as structure, porosity, and degree of compaction. Chemical degradation is not normally detectable by simple inspection, but severe cases of excess salts may be visible on the soil surface.

Nine range condition classes are recognised by Stottart et al. (1975) in rangelands with perennial grasses. Their system can be adapted for sahelian pastoral ecosystems by reducing the number of classes to seven and by redefinition of the their descriptions:

1. Unused. No detectable use by humans or livestock. Grass layer nearly continuous. Palatable grass-layer species probably present.
2. Slight. Traces of use, probably concentrated on palatable species, but vegetation is relatively undisturbed.
3. Light. Palatable species definitely grazed or browsed. Rare or no signs of axe damage to woody plants.
4. Moderate. Palatable species heavily grazed or browsed and less

desireable species definitely grazed or browsed. Few signs of axe damage to woody plants.

5. Close. Stubble in many areas, some patches of naked earth apparently caused by grazing. Desirable grass species absent. Less desireable species heavily grazed or browsed. May be signs of axe damage on many woody plants.
6. Severe. Grass layer represented almost entirely by stubble. Wide patches of naked earth apparently caused by grazing. May be patches of sterile soil and evidence of wind erosion. Signs of axe damage on many woody plants. Some mortality of woody plants. Some indicator species (such as Calitropis procera) may be present.
7. Extreme. Grass layer absent. Frequently patches of sterile soil. Soil structure may be destroyed by trampling. May be evidence of wind erosion or rills.
Near-absence of woody plants or evidence of widespread mortality. Signs of axe damage on most remaining woody plants. Indicator species present.

Condition is also determined by reference to the state of the surface of the soil (see Appendix 3).

It may prove worthwhile to use a standard checksheet in the estimation of condition. A provisional checksheet is given in Annexe 4.

7.2.14 Use by livestock or humans

Forage use is defined as the amount or percentage of current growth removed by grazing or browsing. At the present state of our understanding of range management and the ecology of pastoral ecosystems, this measure is subjective, and is only as good as the experience of the range monitor or manager. A good observer is probably intuitively taking into account the habitual growth-form of the plant under little or no grazing or browsing pressure, its current growing conditions in this habitat with this general range condition, the normal reaction of the species to grazing or browsing, the season, the palatability of the species to different livestock species, and so on.

Given this daunting list, there seems to be little hope for the ecological monitoring unit to achieve the happy state described by Risser (1984:668): "A range manager must know how much of the forage is being taken at any point in time, and also must know how much can be safely consumed without jeopardizing the long-term productivity of the grassland."

No matter how difficult it may be to determine, there is no doubt that use is also one of the most important variables that an ecological monitoring unit can collect in a pastoral ecosystem.

The comparison of plots inside exclosures with plots outside but in similar habitat may go some way toward estimating forage use. Unfortunately exclosures are expensive and extremely difficult to police without full-time surveillance by paid staff (who must not themselves have relatives or own livestock in the vicinity or be susceptible to pressure from local village headmen). Exclosures alter the behaviour of herds, which are attracted to the luxurious growth and then tend to graze and trample more intensively near the fence, so forcing the observer to place comparison plots some distance from the exclosure. Finally, it may be anticipated that species composition in exclosures will not remain identical to that outside the exclosure. This is helpful in suggesting what might happen to the rangeland under reduced livestock densities, but may not necessarily help in the evaluation of forage use.

A method which will probably prove both cheaper and more useful for the grass-layer plants consists of making repeated height measurements along fixed transects throughout the year. Even though the greatest height achieved by the plants, near the end of the rainy season, is certainly influenced by grazing throughout the season up to the time of the measurement, the results of grazing and trampling on the height of the grass layer can at least be monitored for the remainder of the year. It may be necessary to consider the action of the wind in flattening frail, dessicated grasses.

7.3 Purpose and parameters

Table 1 is intended as a guideline for priorities in data acquisition for an ecological unit in the Sahel. Five aims are considered and the parameters necessary to achieve those aims listed. The parameters which are considered indispensible to the aim are marked #, while those which would provide useful additional information are marked with a +.

Table 2 complements Table 1 by suggesting which methods might be chosen for collecting data on a given parameter.

8 Data quality: Duff data, dud decisions.

Allusion has been made on repeated occasions to data quality. Clearly, observers asked to collect information for which they must make decisions that are beyond their comptetence will either refuse, or more likely, do their best to collect the data anyway. Not only will they become frustrated and demoralised, but the quality of their data will be low, and will decrease as their frustration mounts. The resulting information may lead to numbers which, if there are no internal checks on data quality, are faithfully analysed and published. At best it is only the reputation and credibility of the monitoring unit which suffers as other researchers contradict its results. At worst it is the pastures and the pastoralists who suffer as a result of bad policy decisions based in good faith on worthless data.

The responsabilities of the monitoring unit are thus threefold. Firstly, it must ensure that all its operatives are adequately and continually trained by the most experienced members of the team, not only in technique, but in method, and perhaps most importantly, in the aims and objectives of the unit. This training should be designed to give each observer a critical sense of the quality needs of the unit and of his or her own responsibilities and capabilities relative to those needs. Secondly, the unit must only use methods which fall within the competence of the least competent observer who will be required to apply those methods. This may mean limiting the sorts of information which can be collected, and hence the sorts of questions which can be

Table 1: Purpose of inventory or monitoring unit and the corresponding parameters for which data should be collected

Parameter	Basic Inventory	Range Potential	Grazing Capacity	Range Condition
Species composition	#	#	#	#
Cover	#	#	#	#
Height	#	#	#	#
Woody plant basal area	#	#		#
Biomass	#	+	#	#
Vegetative structure				#
Nutritive quality		+	#	+
Vigour		+		#
Reproduction	+	+		#
Phenology		+		+
Frequency		+		+
Topography	#	#		#
Soil erosion	#	#		#
Soil stability	#			#
Litter				#
Water	#	#	#	#
Livestock numbers	#			+
Forage use by livestock	#		#	#

Definitions modified from the Range Term Glossary Committee (1974) and Range Inventory Standardisation Committee (1980):

Range Potential: the capacity of a range to produce livestock, water, fuelwood and any other goods or services required by management plans.

Grazing Capacity: the highest stocking rate possible that will not damage the vegetation or related resources. It varies from year to year with the changes in forage production.

Range Condition: the current productivity of a range relative to what the range is thought to be naturally capable of producing.

Table 2: Methods for evaluating parameters for inventory or monitoring

Parameter	Point Intercept	Variable Radius	Line Intercept	Plot	Literature
Species composition	wg		w	wg	
Cover	wg	w	w	wg	
Height	wg		w	wg	
Basal area		w		wg	
Biomass				wg	
Density	wg		w	wg	
Frequency	wg		w	wg	
Vigour	wg		w	wg	
Reproduction				w	
Phenology	wg		w	wg	
Vegetative structure	*			*	
Nutritive quality					*
Litter	*			*	
Erosion	*		*	*	
Soil stability	*			*	
Topography	*			*	

Key

w = method is suitable for use with sahelian woody species
g = method is suitable for use with sahelian annual grasses
* = method is suitable for parameter

answered. Thirdly, the unit must not only hire a competent statistician to design the methods and analyse the data, but it must try to assess the quality of the results and to show clearly in published reports to what extent the data can be relied upon. If the unit is serving its purpose, it is no exaggeration to say that people's futures may depend upon it.

Part II

9 Introduction: computer simulations of PCQ and quadrat methods

The second part of this document examines the use of the PCQ, plots and strip transects in the monitoring of woody sahelian species. The approach is to use a computer to simulate the habitat and to collect the samples and analyse the results.

9.1 Data used

The distributions of four of the major woody plant species of the western Sahel (Balanites aegyptiaca, Commiphora africana, Grewia bicolor and Acacia senegal) were plotted by ORSTOM in 1974 at a 25ha exclosure near Fété Ole in the Ferlo, North Senegal (Poupon 1980). The distribution of Acacia senegal had been previously mapped in the same exclosure in 1972. Boscia senegalensis was not mapped, although it is abundant in the exclosure. The Pilot Project for the Inventory and Monitoring of Sahelian Pastoral Ecosystems later carried out a similar complete inventory and mapping of the exclosure in 1983.

These mapped distributions of four species at two times separated by less than ten years were set up in data files on a mini-computer and used as the basis of the tests described here.

10 The Point Centre Quadrat (PCQ)

The PCQ is defined in section 5.5 and its derivation set out in Appendix 2. The computer simulations reported here were designed to examine the effectiveness of the PCQ in the estimation of frequency and of density of woody plants in the Sahel.

10.1 Frequency

The PCQ method is widely used to estimate the relative frequency of the various plant species found in a community. If all the individuals in each species in the community are randomly distributed, the method will give accurate results. If, however, we imagine a community which consists of two species with the same absolute density, and therefore the same relative frequency over some given area, but one of which is highly clumped in its distribution, growing only in one restricted part in the area, the other being regularly spaced throughout the area, it is easy to see that a point chosen at random in the sample zone will be more likely to have as its nearest neighbour one of the second species than it is to have one of the first.

Sahelian woody plant species all tend, to a greater or lesser extent, to grow in clumps. Can the PCQ method be used to estimate their relative frequencies with any accuracy? If not, can it at least be relied upon to rank the species in order of their frequency?

10.1.1 Method

A program was written to choose 20 points at random within the simulated exclosure of Fété Ole, and to measure the distance to the closest woody plant of each of four woody species (Balanites aegyptiaca, Grewia bicolor, Acacia senegal and Commiphora africana) in each of the four quadrats around the point. The species of the closest woody plant was recorded.

The procedure was repeated 10 times, and each of the 10 groups of 20 samples was then used to provide a single estimate of the relative frequency (expressed in percent) of the four species. A sample of the output of the program is given in Table 3.

Although the PCQ is a plotless method, the frequency measured by such random location of samples over the 25ha exclosure should correspond to the relative frequency of woody plant species in the exclosure, if the method is to be of use.

10.1.2 Results

For each of the four species, mean estimates of the relative frequency varied widely about the true relative frequency. The results are given in Table 4, and reordered in Table 5, for ease of visualising the spread of the results about the true figure. (The asterisk shows the closest estimate for each species.)

With the PCQ method, four woody plants are scored at each sample point. If 20 sample points are used to estimate the relative frequencies in each sample, the true number of degrees of freedom is 19, and not 79, in each sample, since clumping of the woody plant species means that a "hit" on a given species in the first quadrat increases the probability of a hit on the same species in the remaining 3 quadrats about that sample point. Binomial confidence limits about the estimates are therefore wide (see for example Figure 9 which shows the results for B aegyptiaca), but as a result of this width, the true relative frequency tends to lie within these confidence limits for all four species (not shown). However, these confidence intervals are unacceptably high for most conceivable ecological monitoring purposes, and many more samples would be necessary to increase the precision of the method adequately.

Table 6 shows the deviation of these estimates from the true frequency, each deviation being expressed as a percentage of the true frequency. it should be noted that Grewia bicolor and Acacia senegal, which have the same relative frequency (18%) are not equally well estimated by the PCQ in these simulations. G. bicolor is often overestimated, sometimes largely, while the method seems equally likely to over- or under-estimate the relative frequency of A. senegal; underestimates of this species apparently tend to be very inaccurate. The difference between the response of the PCQ to the two species is presumably due to their obviously different patterns of distribution.

The species with the greatest relative frequency, Balanites aegyptiaca, was always correctly estimated as the most frequent species (Table 7). In 2 out of 10 simulations (3 and 5) the PCQ method established the rank order of the 4 species correctly, and in a further 3 the two species with the same relative frequency (Grewia bicolor and Acacia senegal),

Table 3: Example of output of program to simulate PCQ method of determining relative frequency of 4 sahelian species

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Simulation of PCQ to study relative frequency of 4 sahelian species

Species of the closest tree to the:

Sample	NW	NE	SW	SE	
1	G	B	C	C	
2	B	B	B	B	
3	B	B	B	B	
4	A	A	A	A	
5	G	A	G	B	
6	G	G	G	G	
7	G	C	G	G	
8	B		B	B	'n.b. no closest tree
9	B	B	C	B	in NE quadrat in
10	B	B	B	B	replicate 8§
11	C	C	G	C	
12	B	C	C	B	
13	C	B	B	B	
14	B	C	C	C	
15	B	B	G	B	
16	B	B	G	G	
17	G	B	B	B	
18	C	C	B	B	
19	G	G	B	B	
20	A	B	B	B	

Summary of relative frequencies according to these data:

Number	Percent	Species
82	51.90	Balanites
30	18.99	Commiphora
34	21.52	Grewia
12	7.59	Acacia

Table 4: Results of simulation: Estimates of relative frequency of four sahelian species expressed as percent of total number of woody plants.

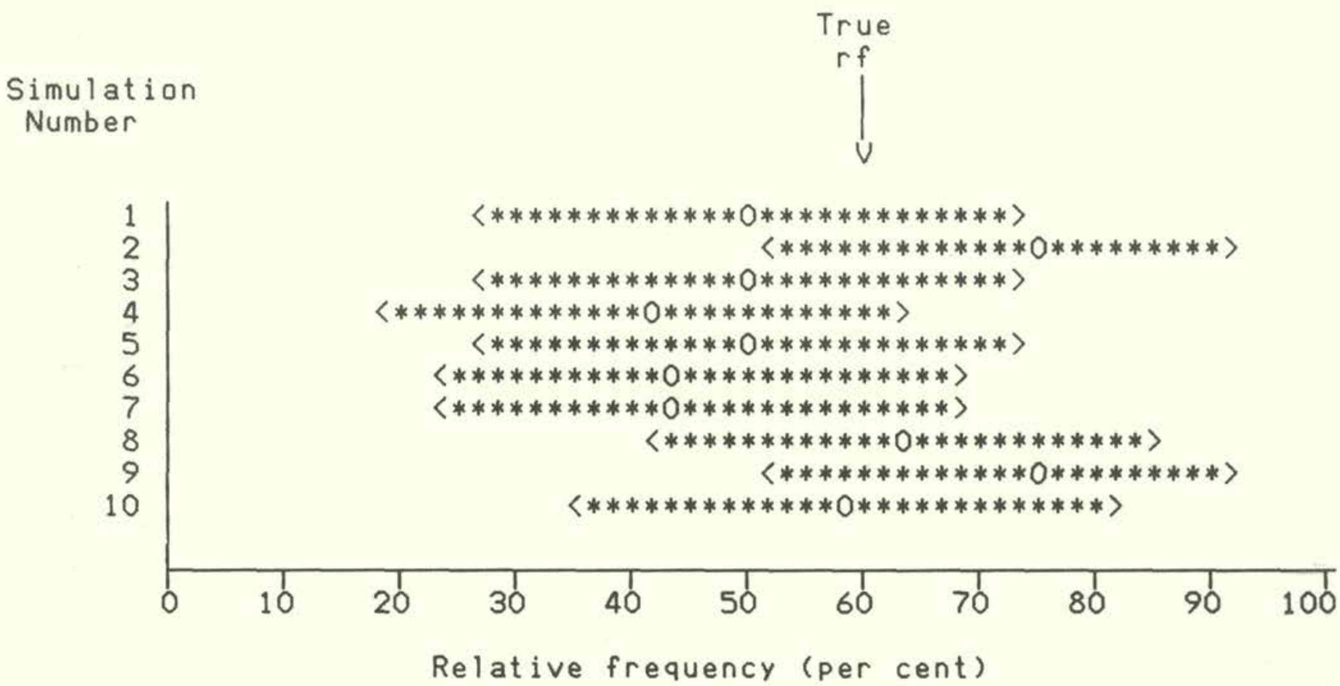
Sample	Balanites	Grewia	Acacia	Commiphora	n*
1	51.90	21.52	7.59	18.99	79
2	75.32	9.09	5.19	10.39	77
3	50.67	20.00	20.00	9.33	75
4	41.56	27.27	22.08	9.09	77
5	51.35	20.27	20.27	8.11	74
6	42.67	32.00	18.67	6.67	75
7	44.74	31.58	17.11	6.58	76
8	63.51	10.81	20.27	5.41	74
9	74.03	12.99	10.39	2.60	77
10	57.89	19.74	17.11	5.26	76

*n should have been 80 in each simulation (20 sample points, 4 quadrats) but is in practice not the same in all cases since some of the random sample points were placed such that in that quadrat there were no trees of any species closer to the sample point than was the edge of the sample zone.

Table 5: Estimates of relative frequency of four sahelian species by PCQ expressed as percent of total number of trees.

	Balanites	Grewia	Acacia	Commiphora
	75.32	32.00	22.08	18.99
	74.03	31.58	20.27	10.39
	63.51	27.27	20.27	9.33
	57.89*	21.52	20.00	9.09
	51.90	20.27	18.67	8.11
	51.35	20.00	17.11*	6.67
	50.67	19.74*	17.11*	6.58
	44.74	12.99	10.39	5.41
	42.67	10.81	7.59	5.26*
	41.56	9.09	5.19	2.60
True relative frequency:	59.75	18.02	17.89	4.34

Figure 9: Binomial 95% confidence limits about the mean estimates of relative frequency (rf) of Balanites aegyptiaca



O represents the mean of 74-79 estimates.
<****> represents the extent of the 95% confidence interval.

Note that the true relative frequency lies within the 95% confidence limits of all of the estimates.

Table 6: Deviation of estimates from true frequency, expressed as percentage of true frequency.

Balanites	Grewia	Acacia	Commiphora
26.1	77.6	23.4	337.6
23.9	75.2	13.3	139.4
6.3	51.3	13.3	115.0
-3.1	19.4	11.8	109.4
-13.1	12.5	4.4	86.9
-14.1	11.0	-4.4	53.7
-15.2	9.5	-4.4	51.6
-25.1	-27.9	-41.9	24.7
-28.6	-40.0	-57.6	21.2
-30.4	-49.6	-71.0	-40.1

Table 7: Rank order of 4 species in 10 simulations of PCQ

	Simulation number										True
	1	2	3	4	5	6	7	8	9	10	Rank
Balanites	1	1	1	1	1	1	1	1	1	1	1
Grewia	2	3	2=	2	2=	2	2	3	2	2	2=
Acacia	4	4	2=	3	2=	3	3	2	3	3	2=
Commiphora	3	2	4	4	4	4	4	4	4	4	4

might have been assessed as having the same rank, having estimated relative frequencies within about 5% of each other. In the other 5 simulations the rank order as determined by the PCQ did not correspond with the true rank order. In particular, the rarest species, Commiphora africana, which was 4 times as rare as the next rarest species, was on one occasion ranked third, and once second.

10.1.3 Conclusions

The results of these simulations of the Point Centre Quadrat method for estimating relative frequency of four sahelian woody species show that the method is highly sensitive to the different spatial distributions of the individual species. As a result, the PCQ can not be recommended in a programme of ecological monitoring for the estimation of relative frequencies of sahelian woody species, nor for the establishment of the rank order of their relative frequencies.

10.2 Density

Since the assumption that species are randomly distributed is clearly unwarranted in the Sahel, the question arises: Can the densities of woody species in the Sahel be calculated within reasonable confidence limits using the PCQ method?

10.2.1 Method

A program was written to select 20 points at random within the exclosure and to calculate the distance to the nearest woody plant of a given species in each of the four quadrats about each sample point. The distance to the nearest woody plant, irrespective of direction, was also calculated. Densities were calculated, using the PCQ formula, from both of these measurements.

Since the underlying assumption of the PCQ method is that the plants are distributed at random, the program was first used on data in which "woody plants" were randomly distributed at densities equal to the true mean densities of the Fété Ole samples. The program was then run using the simulated Fété Ole distributions.

For each species, this simulation was repeated 10 times, giving 10 estimates of the density of that species in the same 25ha exclosure.

Since each of the four test species tend to be found in clumps, most sample points chosen at random will fall outside a clump and lead to low estimates of density. Occasionally, however, a sample point will fall inside a clump, giving an extremely high estimate of density. It seems possible that estimates of density will therefore be log-normally distributed. The program therefore also provided estimates of mean density based on the geometric means of distances and their derived densities.

10.2.2 Results

10.2.2.1 Random distribution of woody plants

In every case, the density calculated from the distance to the woody plant closest to the sample point, irrespective of direction, approached the true density more nearly than did the density calculated from the closest woody plant in each of the four quadrats.

The mean densities from ten trials were close to the true densities. This gives empirical evidence that sufficient samples using the PCQ method will accurately estimate the densities of woody plants distributed at random.

However, even for the closest woody plant, the mean absolute deviation of the ten estimates from the true density was in every case more than 5% of the true density, and for three of the four densities, more than 20% (Table 8). Thus even for woody plants distributed at random, many samples are necessary for an accurate estimate of density.

10.2.2.2 Woody plant species found at Fété Ole

When the simulation was caried out using the model constructed from the recorded distributions of sahelian woody plants, neither the distance to the closest woody plant nor the mean distance to the closest woody plant in 4 quadrats was obviously the more accurate method.

For three species (Commiphora africana, Grewia bicolor, and Acacia senegal in 1972), the mean densities estimated from ten trials are within about 25% of the true densities. For the remaining two species (Acacia senegal in 1974, and Balanites aegyptiaca), the estimates are hopelessly wide of the mark.

It can also be seen from Table 9 that the individual estimates of density were generally inaccurate. That Grewia was estimated so accurately from the mean of 10 trials is apparently accidental, given that the mean absolute deviation of the estimates was 70% of the true density. This is borne out by the individual results of each of the ten trials, given in Table 10.

There are three salient points in Table 10. Firstly, the spread of estimates is typically large, so that any one estimate (based here on the mean of distances from 20 points chosen at random to the nearest woody plant) may be very far from the true density. Secondly, the method sometimes gives estimates that are many times larger than the true density. Thirdly, in this small sample the method gave estimates of density that were lower than the true density 35 times out of 50. In the case of Balanites no estimate was as great as half of the true density.

There were 1429 Balanites stems in the exclosure in 1974, giving a mean of 3.57 stems per block of 25m x 25m. The Poisson distribution with mean 3.57 has its modal value at 3, and the distribution is quite the wrong shape to fit the Balanites data (Table 11). However, simple lack of fit of the data with the Poisson distribution can not be the only reason for the poor estimates; the distribution of Acacia which fits the Poisson least well gives rise to a better estimate of density than does the one with the better fit (Table 11).

Table 8: Estimates of density of randomly distributed stems

True density Stems per ha	Estimated density Mean of 10 trials		Mean absolute deviation (as % of true density)	
	Closest tree	Mean of 4 quadrats	Closest tree	Mean of 4 quadrats
4	3.88	4.63	8.5	15.8
17	19.37	23.99	21.4	41.1
26	24.92	36.48	25.7	40.3
57	62.75	87.03	22.5	52.7

Table 9: Estimates of density of stems distributed as in the Fété Ole exclosure

Species Code	True density Stems per ha	Estimated density Mean of 10 trials		Mean absolute deviation (as % of true density)	
		Closest tree	Mean of 4 quadrats	Closest tree	Mean of 4 quadrats
CoAf	4.12	3.27	3.64	26.2	36.2
GrBi	17.12	17.00	17.50	71.8	57.8
Ac74	17.00	81.30	93.70	400.0	468.2
Ac72	25.64	30.83	37.60	43.6	63.9
BaAe	57.16	18.54	20.40	68.6	64.3

Species Code: CoAf=Commiphora africana
GrBi=Grewia bicolor
Ac76=Acacia senegal in 1974
Ac72=Acacia senegal in 1972
BaAe=Balanites aegyptiaca

Table 10: Results of 10 trials in which density was estimated from distance to nearest tree.

Trial	Species Commiphora	Grewia	Acacia 1974	Acacia 1972	Balanites
1	2.4	6.5	7.6	10.7	10.3
2	2.5	7.4	13.1	13.0	11.8
3	2.8	7.9	14.8	23.3	12.9
4	2.9	8.4	15.1	25.8*	15.0
5	3.0	9.2	16.2	30.0	19.5
6	3.2	9.5	17.2*	32.7	20.2
7	3.3	12.9	20.3	32.8	20.3
8	3.6	13.1*	20.9	35.0	23.8
9	3.8*	43.5	29.5	40.6	25.7
10	5.2	51.6	658.5	64.4	25.9*
True density	4.1	17.1	17.0	25.6	57.2

*For each species an asterisk marks the estimate closest to the true density.

Table 11: Number of 25m x 25m squares containing exactly n stems

n	Balanites Poisson	Balanites Observed	Acacia 72 Poisson	Acacia 72 Observed	Acacia 74 Poisson	Acacia 74 Observed
0	11.2	177	80.6	287	138.2	265
1	40.1	49	129.1	38	146.9	58
2	71.7	27	103.4	23	78.1	39
3	85.4	31	55.3	12	27.6	10
4	76.2	15	22.1	11	7.3	7
5	54.5	22	7.1	3	1.6	4
6	32.4	13	1.9	9		2
7	16.6	12	0.4	4		3
8	7.4	11	0.1	5		2
9	2.9	3	0.0	2		1
10	1.0	6		2		2
Chi sq.		2593		698		201

Estimates of density based on geometric means of distances or of resulting densities were consistently less accurate than were those based on arithmetic means. The only exception in this series of trials was for Acacia senegal in 1974, for which the geometric mean of the 10 values of density gave a better, but still highly inaccurate approximation.

10.2.3 Discussion

Even for woody plants distributed at random, results were disappointing, in that many samples had to be taken before a reasonably accurate estimate of density could be calculated.

For plants with distributions like those of sahelian woody plant species, the PCQ method gave unpredictable results, but may tend to underestimate in most cases, since most sample points fall outside the dense clumps of woody plants, and thus in areas of lower than "average" density. The method wildly overestimates density when the sample point happens to fall in a clump of the species. It is hard to imagine how an ecologist might select sample points in such a way as to arrive at an accurate estimate using the PCQ method, especially since each species will tend to be found in a characteristic distribution, which, at least in the case of Acacia senegal, changes over time. It is also worth bearing in mind that these poor estimates are the result of 200 independant measurements of distance, which would represent considerable work in the field.

Geometric means tend to provide worse estimates than do arithmetic means. Other manipulations of the data might conceivably improve the accuracy of the method.

The question may arise to what extent the computer model biased the results. It is certain that improvements could be made, such as restricting sample points to a central area of a much larger field, thus satisfying the requirement of the Poisson distribution that the forest be effectively infinite. However, it seems unlikely that improvements in the model would greatly change the results.

10.2.4 Conclusion

If woody plants are truly distributed at random, densities calculated from the closest woody plant are better estimates of the true density than are densities calculated from the closest woody plant in each of 4 quadrats. Better results are achieved with a quarter of the work.

For sahelian woody plant species, however, the PCQ method gives estimates that are little better (if at all) than a guess, and should not be used for the inventory of relative or absolute densities of woody species in the Sahel.

11. Comparison of plot and transect sampling for estimating density

11.1 Introduction

In the Sahel many plant species tend to be found clumped in hollows where rainwater collects, while the dune crests are relatively depopulated. The estimated density of most species of woody plant will therefore depend on the position of the sample area relative to nearby hollows and dune crests. Since a strip transect of a given area can be expected to cut across several micro-habitats, while a square or circular quadrat of the same area will tend to sample only one or a few of the available micro-habitats, the strip transect should, for the same amount of effort, give a more accurate estimate of mean density.

11.2 Method

For each trial, a point was chosen at random, but more than 20m from the edge of the exclosure, and the number of woody plants of a given species within a radius of 20m counted. The process was repeated for plots of radii of 40, 60, 80 and 100m. These radii correspond to areas of roughly 0.125, 0.5, 1.1, 2.0 and 3.1 hectares respectively. From other points chosen at random, lines were drawn east-west across the width of the exclosure and all the woody plants of the same species within 1.25, 5, 11.3, 20.1 and 31.4m of the given line counted. Since the exclosure is 500m across, these strips enclosed the same areas as those enclosed by the circular plots. One hundred such trials, grouped in sets of 10, were carried out for each species. The program calculated the mean and standard deviation of the resulting ten estimates of density for each species and each area.

Identical procedures were first carried out for theoretical species in which stems were distributed at random but at the same densities as the sahelian species, and second using the simulated sahelian species distributions. This provided results against which those drawn from sahelian plants could be compared.

11.3 Results

11.3.1 Randomly distributed stems

Neither the strip transect nor the circular plot had an obvious advantage in either the precision or the accuracy of estimates of the density of stems scattered at random.

As might be expected, the smaller the area sampled, the wider was the spread of estimated densities, and hence the larger was the standard deviation of the estimates expressed as a percentage of the true mean.

As a corollary to this, as the density of woody plants increased, so the spread of estimates about the mean decreased.

11.3.2 Sahelian woody plants

Estimates of the density of sahelian woody plants tended to be both less accurate and less precise than were estimates of the density of stems distributed at random.

As is the case for stems distributed at random, the smaller the area sampled by a circular plot, the wider was the spread of estimated densities. By contrast, at low sampling intensities, the strip transect consistently underestimates densities, but increasing the width of the strip sample increases its accuracy.

For Grewia bicolor, most of the 10 mean estimates of density at each sample size, and irrespective of the method used, fell below the true density. This result should of course be expected for all species which tend to grow in clusters.

In general, were we to use the median of 100 samples of the density of woody plants in the exclosure at Fété Ole, by whichever of the two methods, we would tend to underestimate the density of Grewia, Acacia, and Balanites. In particular, the strip transect tended to severely underestimate densities at low strip widths, but increasing the width of the strip transect greatly reduced the risk of underestimation for all species. For Grewia and Acacia, increasing the size of the plot searched did not greatly change the tendency to underestimate density.

If the strip transects tended to underestimate densities at low strip widths, because woody species were thinly scattered over most of the area sampled, the plots occasionally severely overestimated density, especially when the area searched was low, because the centre of the plot sometimes fell close to a clump.

For any given sample area, strip transects gave more precise estimates of density than did circular plots. The relationship between precision (defined as the standard deviation of the samples expressed as the percentage of the true density) and sampling effort (defined as area searched) decreased rapidly for circular plots, and less rapidly for strip transects. Thus with strip transects there was in general little extra precision to be obtained in the estimate of the density of any of the species by increasing the width above 22.6m (corresponding roughly to 1 hectare). By contrast, precision continued to increase with increasing sampling effort (up to a radius of at least 100m, representing 3ha) for all the species whose density was estimated using circular plots. It should be noted in passing that the relatively low standard deviation of narrow strip transects is of little practical interest, in view of the extreme inaccuracy of the estimates at these strip widths.

Irrespective of the method used, the densities of some species were estimated with higher precision than were those of others, but this did not depend directly on the density of the species concerned. Thus, for large sample areas, the density of Commiphora africana tended to be estimated more precisely than did the density of the other species, though it was the species with the lowest true density.

By comparing the mean and variance of the difference between each of the 10 mean estimates at each sampling density and the true density of the plant species concerned, it is possible to judge which of the two methods is more likely to give an accurate result at any given sampling density for each of the species tested. Table 12 shows the probability (t-test) with which one can state that one or the other of the two methods will tend to give a more accurate result.

Table 12: Comparison of accuracy of
Strip transects (S) and Circular plots (C):
Results of t-test.

	Area sampled (Ha)				
	0.125	0.5	1.1	2.0	3.1
Commiphora	CCCC	CCCC	CC	SSSS	SSSS
Grewia	CCCC			SS	SSSS
Acacia (72)	CCCC	CC		SSS	SSSS
Acacia (74)	CCCC	CCCC			SSS
Balanites	CCCC	CCC	CCCC		SSS

Key: The S or the C shows for which method the mean estimate was closer to the true density. The number of symbols gives the value of p; 1 symbol represents a p of less than 0.05, 2 symbols less than 0.025, 3 less than 0.01, and 4 less than 0.005.

Note that although small circular plots give more accurate estimates of density than do narrow strip transects, the estimates are not good. Areas of at least one hectare, and preferably more, should be sampled.

11.3.3 Discussion and Conclusion

In the simulation, 100 estimates were made of the density of each species using each method. In practice, probably only one or two estimates would be made in any given area. Any single estimate of density, of any of the species tested here, by either of the two methods is likely to be a poor estimate of the true density. Areas of less than about a hectare, whether searched by counting in a plot or in a transect, will provide very little information about the density of sahelian woody plants, or of species composition, in the surrounding area. Very large areas undoubtedly give better estimates, although the amount of work involved in sampling such large areas may be unjustifiably high. It is worth pointing out in this context that in the area of Fété Ole in 1984 there was a mean of about 460 woody plants per hectare (roughly 350 Boscia senegalensis, 50 Balanites aegyptiaca, 46 Guiera senegalensis, 6 Grewia bicolor, 3.5 Acacia senegal, and 3.6 others).

In some areas of the Sahel there is a clearly defined difference in the density of woody plants growing on the dune crests and in the troughs. In these areas, stratified sampling in the two zones will certainly give more accurate results than will non-stratified sampling. Such stratified sampling will also provide information on habitat preferences of the different species which would not be available in a non-stratified sample. However, in many areas, as at Fété Ole, the hollows and domes are arranged in such a haphazard way that determining the percentage of ground in the two categories may pose problems of its own.

If an accurate estimate of density is needed - for example, if the work is intended to provide a comparison of density between areas - probably the best technique is to take the mean value from several long strip transects each covering at least a hectare. If considerations of time or labour mean that smaller areas are to be searched, circular plots, of about a hectare in area, probably provide the most economic and reasonably accurate estimate.

For monitoring purposes, the absolute density of woody plants is less important than is the trend in the density with time. In this case, the method of choice is certainly to use a circular plot, of a hectare or more, whose centre has been marked accurately. Its radius should be measured with an inelastic cord or wire. The measurement can thus be repeated year after year on the same site, with very little chance of sampling the wrong area by mistake - which would be more difficult to ensure with strip transects. However, if there is reason to believe that the marker will be removed or lost between years, then long strip transects covering about a hectare are more likely to be sensitive to changes in density than are circular plots of equivalent area whose centres vary from year to year.

12 Summary and Discussion

12.1 Results cost time and money

The collection of data in the field is expensive and time-consuming. At least half of the cost of an ecological monitoring unit should be budgeted for collecting ground data, and at least one third of the time of staff members will probably be spent in the field. Costs may be marginally reduced by locating the unit's headquarters in or as close to the study zone as possible, or alternatively by renting accommodation and office space for a field station in the zone.

Clearly the samples collected in the field should be designed to give the greatest possible amount of information for the effort involved. However, if the method is too complicated it is unlikely that it can be repeated elsewhere or even from year to year at the same stations. Sampling in the field is therefore the financial and manpower bottleneck for most ecological monitoring programmes: data collected by low-level reconnaissance flights follow simple set rules (see GEMS 1986c), while satellite data can be examined at leisure in the office.

12.2 Time and money spent on design of sample is investment

Misleading results are worse than useless. Since the value of quantitative data on the composition of vegetation depends on the sampling procedure used to obtain them, the initial effort expended in conceiving, setting up and testing a sampling strategy should be seen as a vital part of the work of the unit.

Having decided on the aims and means of the unit, one of the first tasks is to stratify the area in which sampling will take place. Although the limits of the various strata are to some extent subjective, various methods exist to aid in the decisions. If there is any doubt it is always better to stratify the area (work load permitting) before sampling than to assume that the area is homogeneous. Samples can always be lumped, but it is unlikely that data can later be divided into separate parts corresponding to the strata in the field.

12.3 Testing design in the field

The unit should expect to spend at least one field season in testing and refining the sampling design. For certain parameters the time spent improving and streamlining the design may extend to several years.

12.4 Testing design by computer simulation

If initial field data are collected in the field giving the unit information on the distribution of the parameters of interest, it should be possible to set up computer simulations of various sampling designs to test their efficiency, precision and accuracy. This approach has the advantage that radically different designs can be tested at little cost and no risk, and the work should lead to a short-list of designs to test in the field.

12.5 Analysis

Expensive data deserves quality treatment: the analysis should be as good as the data can support. Inventory and monitoring are expensive, and investment in a micro-computer and associated software will represent a tiny part of the budget, but a major improvement in the possibilities and quality of analysis. At current prices, the cost of the software will probably be of the order of three to five times the cost of the hardware. Nevertheless, some programs will certainly be written by project staff for particular project needs, and it will be necessary to hire a programmer as well as a statistician for the data treatment and analysis.

12.6 Reports

The worth of a document is often assessed on first impressions. A report that is well-presented, with neat layout and attractive diagrams will dispose the reader to treat its contents with interest and respect. If the reader finds that the document is not only well presented but written clearly, in an unpretentious style, and that the ideas it contains are communicated easily and naturally, he or she will no doubt refer to it often. If, on the other hand, the reader must work to understand it, there is a good chance that it will be pushed aside and the information it contains is then effectively lost.

The reputation of the ecological monitoring unit can therefore hinge on its publications. Timely, high-quality contributions to the literature on rangeland monitoring will encourage respect and, it is to be hoped, action.

Appendix 1a: Standardizing data collection: Paragraph 2.6.7 of The Handbook of Ecological Monitoring (Ed Clarke 1986)

Every vegetation monitoring programme should have a library of standard forms that are used at different stages of data collection and analysis:

1. Methods forms outline, in a step by step fashion, how each procedure is used to collect data in the field. Every person newly incorporated into the programme should make initial field trips with an experienced person and should carry out these methods until the methods are thoroughly understood.

2. Data collection forms should be standardized for each monitoring technique so that the data are always collected in the same format. These forms should contain unique information about each sample such as date, time, and location of sampling, and should provide a space for general observations about the data sampled. They should be set up in tabular form so that each data entry of a given type goes into exactly the same space for every sample.

3. Data reduction forms are used back in the office, after data has been collected, to perform initial analyses of the data such as calculating means, variances, and other properties of the samples. They should be a means of initially consolidating the data from several samples into a common summary format.

4. Final summary forms should be designed to condense the data from several forms into summary statistics that reveal the overall patterns being monitored. These forms will provide the information used in interim and final reports.

When a vegetation monitoring programme is planned and implemented, it is essential that each participant understand at the outset exactly how the data are to be used and what their final form will be. The project managers, in particular, should have a very clear understanding of how each type of data is going to be summarised and analysed, and what its function is within overall monitoring goals. It is not sufficient to collect data and hope that its analysis will reveal something of interest.

Appendix 1b: Commentary on Standardizing data collection

Ecological monitoring units typically collect and analyse such quantities of data that the use of a micro-computer is now almost indispensible. At the same time that the price of such machines is coming down, their capacities and capabilities are rapidly increasing.

Small battery-operated laptop computers may be specifically programmed with software designed to allow data to be keyed directly into the machine in the field (Harding pers comm.) The "data collection forms" referred to above are then replaced by standard menus or serial prompts as appropriate. Some interactive editing facility is indispensible.

Most units will not yet possess computers suitable for data-collection, and will continue to collect field data with checksheet and pencil. Information recorded on correctly designed data collection forms can be keyed directly into a computer in the office. The "data reduction forms" referred to in paragraph 3 above may therefore be created automatically by custom-written software as part of the data input and validation stage. Similarly, final summary forms could well be created by the final program in the suite of analysis software.

Appendix 2: Derivation of formula used in PCQ method (Pollard 1979)

Assumptions of the model:

1. Stems are distributed at random.
2. Density of stems is uniform when large enough areas are considered.
3. The field area is effectively infinite.

If the distance from the sample point to the nearest tree is r, then there is a ring around the sample point of width dr and area (2*pi*r)dr which contains exactly one tree. If the density of trees is D then, from the Poisson distribution, the probability of an area (2*pi*r)dr containing exactly one tree is (2*pi*D*r)dr. There is an area A=pi*r^2 around the point in which there are no trees. Again from the Poisson distribution, the probability that an area A contain no trees is p=exp(-AD). From these two independant probabilities, the mean distance d to the nearest tree is

$$d = 2*pi*r^2*D*exp(-DA)\ dr$$

$$= 2*pi*\Gamma(1+1/2) / (2*(pi*D)^{(3/2)})$$

$$= 2*pi*D*(1/2)*pi^{(1/2)} / (2*pi*D/pi^{(1/2)}/D^{(1/2)})$$

$$= 1/(2*D^2)$$

therefore $D = (1/2d)^2$

This is the formula relating the density of trees in the area to the mean distance to the closest tree irrespective of direction. If the distance to the nearest tree in each of 4 quadrats is measured, the original equation becomes

$$d = 2*pi*r^2*(1/4)*D*exp(-DA/4)\ dr$$

leading to $D = (1/d)^2$

Appendix 3: Indices of soil degradation

A3.1 Biologically degraded earth

There are two main indicators of biologically severely degraded soil in the Sahel.

A3.1.1 Indicator species

Zornia glochidiata grows in abundance, almost to the exclusion of other species, in areas of intense degradation and loss of soil structure near livestock troughs.

Calitropis procera grows typically in soil that has been cultivated and exhausted and in areas of heavy overgrazing, often near villages or camps.

A3.1.2 Algal growth on crusted soil

In the sandy Sahel a blackish Cyanophyces algae (genus Scytonema) sometimes grows on crusted soil. These algae form a hydrophobic layer making the soil impermeable to rain and hence rendering it sterile. This latter condition can be detected by the crusted, naked soil surface, slightly darker than the underlying sand.

A3.1.3 Termite mound remains

Some soils show spotting of circular whitish patches on which no plants grow. These are the traces of old termite mounds and seem to resist colonisation by sahelian plants, probably because of the compaction and cementing of the soil.

A3.1.4 Soil structure destroyed by livestock

The areas of loose deep sand mixed with powdered dung found near points of intense livestock concentration and the loose sand of major livestock trails indicate heavy use and mechanical degradation of the environment. The surface extent of these severely downgraded areas is normally limited and the direct ecological implications are not in general serious. The presence of such areas may however indicate overgrazing in the immediate vicinity.

A3.1.5 Heavy grazing

Areas can become denuded by overgrazing, especially in the late dry season. Signs of such overuse may include some remaining short stubble at ground level, exposed grass roots, and numerous hoofprints or other indications of disturbed soil surface.

A3.2 Erosion

A3.2.1. Water esosion

The evidence of water erosion is most clear just after a rainstorm, and includes muddy streams form during the storm, and signs of soil deposits at the base of slopes. Specific types of water erosion can be detected:

A3.2.1.1 Gully or rill erosion

Gulleys and rills are often found near to or in firebreaks and fields, and may be spectacular in stream beds near villages in areas with gravelly soils. Rills in sandy soils are often rapidly obliterated by the action of wind and livestock. In areas of relatively severe gulley erosion the roots of bushes and trees may be exposed (see wind erosion).

A3.2.1.2 Sheet erosion

There are six relatively easily recognisable indices of sheet erosion:
1. Stones are perched on pedestals of earth. The surrounding soil surface has been removed to the depth of the pedestal.
2. Grit and stones are found resting on the surface, while the sand and fine soil particles has been removed from the soil (see wind erosion).
3. Plants are typically perched on hummocks. This structure may also be seen in the healthy situation where plants are raised up on accumulations of plant detritus, or in the unhealthy case of soil accumulation brought in by wind erosion elsewhere.
4. There is evidence of accumulation of earth uphill of obstacles and its disappearance downhill.
5. In some areas the underlying iron hardpan is exposed by erosion (or rarely other processes). These patches of laterite are unlikely to support plant life of any consequence to the livestock in the near future.
6. Plant litter is removed from definite patches and is accumulated in small snaking dams between 1 cm and 5cm high.

A3.2.2 Wind erosion

FAO/UNEP/UNESCO (1979) shows that most of the Sahel is subject to wind erosion. The clearest evidence of wind erosion is to be found before the first rains, and includes:
1. Local dust- or sand-storms, and dusty whirlwinds.
2. Saltation of sand grains in strong winds. Moving sand may form curtains of sand which snake across the surface in the wind.
3. Wide areas covered by plaques of compacted naked soil whose upper sandy layer has been scoured off; the downwind side of these areas are often rimmed by ripples of loose sand or by packed sand at the base of plants.

Sandy areas may become sterile as naked earth is exposed to rain, and the smaller clay-sized particles in the upper layers wash down to a lower layer where they form a dense mass. The larger sand grains above this dense layer are then blown away leaving the dense mass to crust in the sun. Subsequent rain runs off the crust and the seeds under the crust never germinate. This condition is easily detected by the compact laminar structure of the soil surface, which makes it possible to break off plates of coherent sand from the upper crust.

4. Grit and stones lying on the soil surface, the sand and fine soil having been blown off (see water erosion).

5. Ripple marks in loose sand or tiny dunes of loose sand formed on the smooth surface of hard crusted sand.
6. Formation of sand-sheets, mini-dunes or dunes. In areas in which agriculture has been attempted, the sand-sheets may obliterate all traces of the fields and nearby tracks, leaving only the tops of cut branches to indicate the lie of hedges.
7. Accumulation of sand behind hedges, tree trunks and other obstacles. The deposit is normally rounded upwind of the obstacle and pointed on the downwind side. Near hedges there are often clear wind-channels cut through the sand deposits.
8. Uprooting of trees and bushes in zones of deep non-compacted sand.

While much of the Western Sahel experiences dry haze (or "brume sèche", as it is called in francophone Africa), which may reduce visibility to a few tens of metres, this phenomenon is not a good indicator of deterioration of the local ecosystem. Its origins may be many hundreds of kilometers from the afflicted area (Kalu 1979).

A3.3 Condition of the soil and litter

Stoddart et al (1975) have classed soil and litter conditions into five groups, which emphasise the effects of water erosion in soil degradation. In the Sahel, where water erosion is less in evidence than wind erosion, the classes of degradation might be:

1. None.	No evidence of soil movement. Top soil layer intact, containing organic detritus and overlain by well-dispersed litter from previous year.
2. Minor.	Difficult to recognise soil movements. Where detected, some small rills ending in fans, accumulations upslope or downwind of plant stems or litter. Litter sporadically dispersed, accumulating against obstacles.
3. Evident.	Soil movement noticeable. May be pedestals or hummocks around stems of plants. Ripple marks or rills may be present. Poorly dispersed litter. Bare spots.
4. Advanced.	Soil movement clearly recognizable. Roots exposed or stems buried. Ripple marks near large patches of bare earth. Sand accumulated behind obstacles. If relief detectable, upwind slope may show large scoured areas and downwind slope loose sand. Where present, litter washed or blown into patches.
5. Severe.	Large areas of naked earth in dry season. In areas of sufficient relief, active gullies with steep walls in wet season. Erosion pavement or hardpan exposed on gravelly soils. Litter mostly absent. In dry season, blowing sand moving over soil surface in strong breeze. Woody plants may be uprooted or partially buried.

Appendix 4a: Suggested checksheet for assessment of range condition.

This checksheet is a preliminary guide to classification of a sample site. If assessments of range condition are required it will be necessary to standardize subjective assessments. This checksheet is intended to help in the standardisation by listing the various components by which condition may be judged.

After filling in his or her name and the date, the observer notes the site number or identifier and then, using the guide to classification on the next page, assigns a number (0-5) to the cover of the grass layer. Other boxes in the same column are successively filled in with the appropriate scores. It will be seen that high numbers indicate poor condition. If desired, a single score can then be given to a site, which may be the total of all the individual scores (in which case a site in excellent condition will be rated 0, while one in appalling condition might be rated in the high 30s - the top score of 41 being highly unlikely). A single score could also be constructed by weighting the relative contributions of the different components: thus vegetation parameters might be weighted more heavily than soils for a particular application. Partial scores, totalled seperately for vegetation and soils, convey additional information which may be important to the user of the data.

Observer: ____________________ Date:_____________

Site Number:											
Grass layer	Cover										
	Use										
Woody plants	Regeneration										
	Use by humans										
	Use by livestock										
Litter	Dispersion										
Soils	Permeability										
	Organic cont.										
	Structure										
Erosion	Wind										
	Water										

Appendix 4b: Guide to classification of ecological condition of a sample site in the Sahel

Grass layer

Cover

0. Continuous (patches of bare earth less than 5%)
1. Threadbare (bare earth 5-25%)
2. Patchy(bare earth 25-50%)
3. Discontinuous (bare earth 50-75%)
4. Spotty (bare earth 75-95%)
5. Absent (bare earth 95-100%)

Use

0. Unused.	No detectable use by livestock.
1. Slight.	Traces of use, concentrated on a few species.
2. Light.	Some species definitely grazed.
3. Moderate.	Some species heavily grazed.
4. Close.	Stubble in about half of the grassed areas.
5. Severe.	Grass layer almost entirely stubble.

Woody plants

Regeneration

0. Full.	Seedlings of all major woody species found.
1. Selective.	Seedlings and young plants of some species.
2. None.	No evidence of seedlings.

Use by livestock

0. Unused.	No detectable use by livestock.
1. Slight.	Traces of use, concentrated on a few species.
2. Light.	Some species definitely browsed.
3. Moderate.	Some species heavily browsed.
4. Close.	Leaves missing or severely damaged in about half of the woody plants
5. Severe.	Leaves missing or severely damaged on most or all palatable species. Twigs damaged.

Use by humans

0. Unused.	No detectable use by humans.
1. Slight.	Some axemarks, concentrated on a few species.
2. Light.	Branches of some species lopped.
3. Moderate.	Some species heavily axe-damaged.
4. Much.	Axe damage to about half of the woody plants.
5. Severe.	Evidence of felling, most remaining woody plants axe damaged.

Litter

Dispersion

0. Even.	Well-dispersed, no clear patches
1. Irregular.	Sporadically dispersed, small areas of cleared soil
2. Poor.	Large areas swept clear, some accumulations.
3. Disturbed.	Litter washed or blown into small dams against obstacles. Most areas free of litter.
4. Removed.	Litter mostly absent.

Soils: Appearance of most of the areas of bare soil at the sample site

Permeability:
0. permeable
1. hard packed earth
2. crusted and sealed soil surface

Organic content:
0. present; includes litter and many seeds
1. present but few seeds
2. reduced
3. very little or none

Structure:
0. apparently intact
1. apparently disturbed
2. none: eg hardpan exposed or soft blown sand

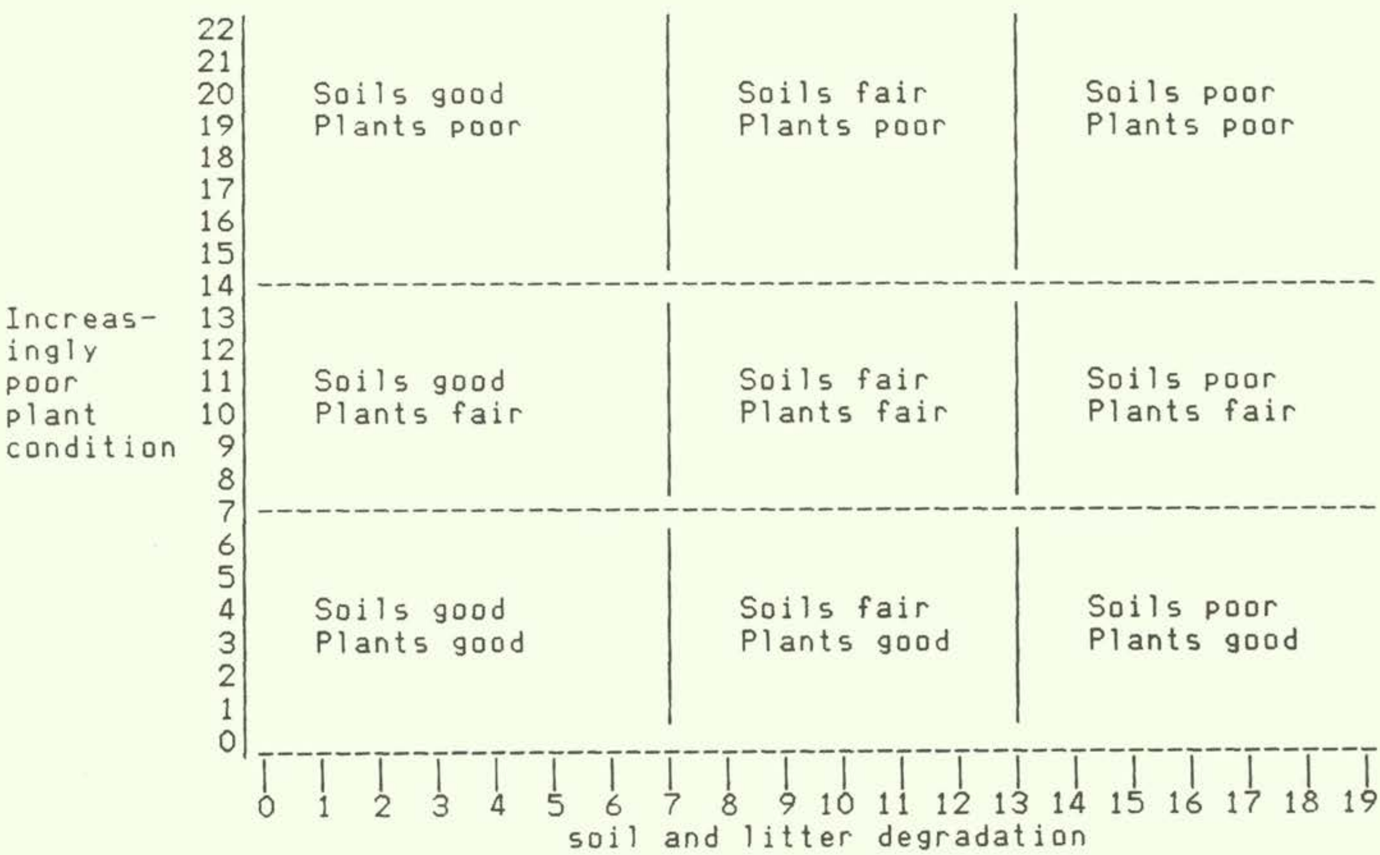
Wind erosion

0.	None.	No evidence of wind-induced soil movement.
1.	Slight.	Detectable accumulations downwind of obstacles.
2.	Moderate.	Ripple marks in sandy areas.
3.	Much.	Ripple marks, scour, accumulations of loose sand
4.	Severe.	In dry season, blowing sand moving over soil surface in strong breeze. Woody plants may be uprooted or partially buried by soft sand.

Water erosion

0.	None.	No evidence of water-induced soil movement.
1.	Slight.	Detectable accumulations upslope of obstacles.
2.	Moderate.	Rills in areas of relief. Rocks and plants on small pedestals
3.	Much.	Roots exposed; rills, pedestals pronounced.
4.	Severe.	Gulleys or clear evidence for sheet erosion. Woody plants undermined and toppling or fallen.

If desired, each site could be located on a two dimensional graph, with vegetative condition (scores for grass layer + woody vegetation) on one axis and soil and litter condition on the other axis.



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Substantial bibliographies are appended to several of the papers or books in this list. Of special note:

Grieg-Smith P. (1964) lists some 480 titles of direct interest to the design of vegetation sampling.

Mueller-Dombois D. and H. Ellenberg (1974) include about 440 titles concerning classification, sampling and analysis of vegetation. Many of the papers listed are written in German or French.

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