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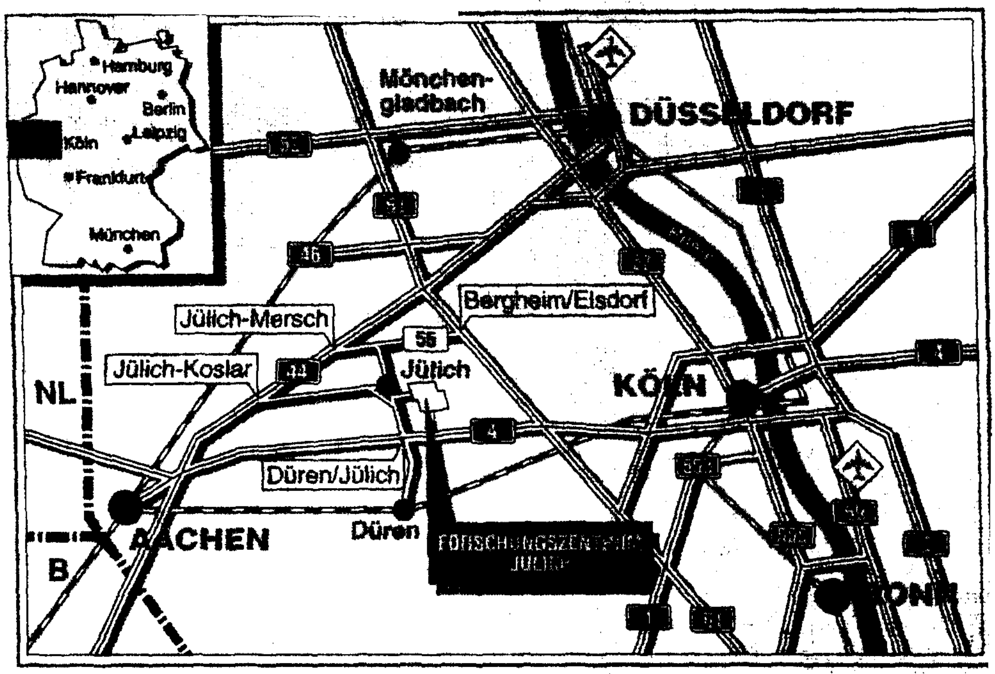

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Limiting Climate Change
Verification of compliance with treaty commitments to limit greenhouse gas emissions from forests and land use by remote sensing

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PREFACE

About 150 states, among them the Federal Republik of Germany, signed the Framework Convention on Climate Change at the United Nations Conference on Environment and Development in Rio in 1992. This convention is the first step on the way to a climate protection regime: Further protocols should be negotiated and signed by as many states as possible in order to freeze their CO_2 emissions or even reduce them by a defined amount and to progressively terminate the destruction of the forests. Other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) can be included in further protocols at a later date. A model for such international action is the "Vienna Convention for the Protection of the Ozone Layer", its "Montreal Protocol" and the following amendments.

In negotiations on these treaties the states will have to clarify whether they intend to take the legal, institutional and instrumental steps required in order to verify whether all state parties have really met their obligations with respect to emission reduction and protection of the forests (verification of compliance).

On the German side, preparatory work for a verification system is being carried out inter alia within the framework of the BMFT/IKARUS project set up in October 1990 for a period of four years. The aim of the project is to develop tools for national climate gas reduction strategies. These tools comprise a data base with technical, ecological and economic data on present and future components of the German energy system as well as a simulation and optimization model drawing on this data base. KFA-TFF is responsible for the overall project management and for Subproject 9 "International Greenhouse Gas Verifications", which forms a link between the IKARUS project and international efforts at emission reduction.

In searching for models of international verification systems in other issue areas, arms control inevitably comes to mind and, in particular, the safeguards of the International Atomic Energy Agency (IAEA) under the atomic Non-Proliferation Treaty (NPT) and the new convention on the Prohibition of Chemical Weapons. In analysing these verification areas, three factors of influence seem to be of particular significance, i.e. verification suitability, verification capability and verification density.

- The verification suitability of an object, a sector etc. subject to safeguards is of a systematic nature. This verification suitability results from the structures, characteristics and configuration of the object to be monitored.

- The practical implementation of a verification system finally depends on the availability of qualified staff resources and adequate methods, equipment and tools in order to implement the verification measures with the required sensitivity and accuracy. These requirements are referred to as verification capability.

- The verification density is determined by political driving forces. The greater the certainty is to be that other countries have complied with the provisions of a treaty, the closer must be the verification of their actions. The verification density must be increased.

In order to agree on a practical verification system, these essential factors and peculiarities must be analysed and defined for each individual greenhouse gas and emission sector. In detail, this results in the following tasks:

- defining the political verification requirement
- analysing the characteristics of emission sources
- examining the quantitative recording of greenhouse gases
- reviewing institutional aspects of verification
- identifying and evaluating the verification tools
- providing a synthesis of these activities and developing verification concepts.

In all these areas, studies under the IKARUS project are also carried out in cooperation with institutions abroad and published in the series "International Greenhouse Gas Verification". The following study has been prepared by VERTIC/London, UK, and deals with the application of remote sensing satellites for greenhouse gas verification.

G. Stein

Executive Summary

Introduction

This report contains the results of a study of how to verify compliance with treaty commitments to limit anthropogenic greenhouse gas emissions. The study concentrated on establishing methods of verifying compliance with the Framework Convention on Climate Change. In particular, it examined methods of monitoring commitments to limit anthropogenic emissions from forests, agriculture and waste (for example, landfill sites) rather than from fossil fuel burning, which has been the subject of other detailed studies.

Background and basis for the work

Verification of compliance with international agreements must be carried out at a national level, because nation states are the parties to such agreements and it is their compliance with their commitments that must be checked by any verification regime. Therefore, it is essential that any verification regime is able to measure the amount (preferably the mass) of greenhouse gas which is anthropogenically generated within each nation which is party to an agreement to limit emissions of them. Also, because gases disperse rapidly in the atmosphere, it is necessary to monitor emissions at their source. The first task in the study reported here was thus to identify emission sources.

The main anthropogenic greenhouse gas emission sources, other than those associated with fossil fuel burning, are given in the table overleaf. The sources are categorised into three main 'sectors', the titles of which reflect the origins of the emissions. The sectors are: forests, agriculture and waste. Within each of the sectors some of the more important features of the different types of source which might have a bearing on how they might be measured are given - for example, the size and numbers of sources are indicated, in general terms. The second main task of the work reported here was to determine how to measure the sources listed in the table.

SECTOR		SOURCE CHARACTERISTICS									
Sector	Sub-sector	Size of sources		Number of sources		Continuous or intermittent		Mobile or static		Point or diffuse	
		Big	Small	Many	Few	Cont.	Int.	Mob.	Stat.	Point	Diff.
FORESTS	Clearing	✓			✓		✓	✓			✓
	Selective cutting		✓	✓			✓	✓			✓
AGRI-CULTURE	Rice Paddies		✓	✓			✓		✓		✓
	Ruminant		✓	✓			✓	✓		✓	
	Fertiliser		✓	✓			✓	✓			✓
WASTE	Landfill		✓	✓		✓			✓		✓
	Other		✓	✓		✓			✓	✓	✓

It may be seen from the table that most of the sources under consideration in the study were likely to be difficult or expensive to measure using *direct* methods (that is, by standard mass flow techniques which are best suited to measuring fluid flow in well defined spaces - such as pipes). The majority of the sources are either diffuse or intermittent or both, which tends to make them difficult to measure from a technical standpoint. Also, there are typically many, small sources in each sector, which implies that monitoring them all would be expensive.

In light of the technical and economic difficulties associated with monitoring emissions using *direct* measurement methods, this study concluded that it would generally be more practical to use *indirect* emission measurement methods for verification related monitoring. (An indirect measurement is one in which the amount of gas emitted from a sources is calculated from two or more other measurements which at some stage involve direct measurement - for example, indirect measurement of emissions from vehicle exhausts is possible by calculation from the fuel consumption of the vehicles and data on the combustion efficiency of their engines.) The exception to this general conclusion is that it would be simpler to monitor emissions from landfill sites using direct measurement methods.

Indirect emission measurement methods are most accurate when i) they are calculated from accurate data and ii) if their calculation involves few stages of computation. Ideally, they are made by calculation from only two sets of data: a directly measured parameter and a generally applicable *emission factor*. However, in the emission sectors of interest in this study, it was usually difficult to establish both an accurately measurable parameter and an correspondingly accurate emission factor. Thus, although indirect measurement methods would enable most emissions from the sectors to be measured, they would not usually allow accurate measurements to be made - mainly because of difficulties in establishing accurate, generally applicable, emission factors.

To overcome the problem of obtaining accurate data by indirect measurement methods, this report concludes that any treaty commitments to limit greenhouse gas emissions from the sectors under consideration should *not* be specified in terms of emissions but in terms of a directly measurable parameter from which emissions could be calculated. This approach would, to a large extent, circumvent the difficulties associated with deriving accurate emission factors. In practice, it would result in emissions from forests and rice paddies being specified in terms of their area and type, emissions from ruminants being specified in terms of their numbers, and emissions from fertiliser use being specified in terms of the mass of materials applied to fields.

The bulk of this report is devoted to detailing how to verify commitments made in the manner outlined above. The report concentrates on satellite based remote sensing methods, because these have a number of fundamental advantages over other verification related monitoring methods that might be used for this purpose - in particular, they can be independent of restrictions due to national sovereignty, can provide data of uniform quality to all parties to an agreement and could be independently controlled by an internationally based verification body. Remote sensing methods are not suitable for monitoring emissions (or related parameters) from landfill sites or fertiliser use and these topics are thus discussed separately.

Resources for monitoring compliance

The study reported here assumed that implementation of commitments made under the Climate Convention would be monitored primarily at a national level and reported to the Conference of the Parties to the Convention in the form of 'national reports', as laid down in the Convention. If compliance with national commitments was to be verified, it was taken that two other sets of data would be required: one comprising data on emissions (or parameters relating to them) at the time of the agreement coming into force (baseline data) and another independently gathered set of data to monitor changes from the baseline. (The second set of data would be collected at regular intervals and would enable checks to be made on the veracity of national reports.) Means of collecting and storing both of these types of data were investigated in detail.

The reliability of any monitoring system designed to measure changes in areas or numbers is absolutely dependent on the accuracy and reliability of the baseline data from which the changes are measured. As complete and accurate a record as possible is thus required. If verification related monitoring is to be effective the baseline data must not only be accurate and comprehensive but it must also be available in compatible formats and must distinguish between anthropogenic and natural changes.

The study found that several large databases of the basic type required for compiling baseline data on forests and agriculture already exist, most being based on data gathered by the Food and Agriculture Organisation (FAO). Both the amount of data and the size of the databases would however have to be expanded considerably if they were to be of use in this application.

As part of the study, a specification was drawn up for a space based remote sensing system. To be suitable for verification related monitoring of changes in land use areas any space based system should meet this specification. In brief, the specification stipulates that such a system should comprise at least two satellites: one giving frequent, low resolution views of the entire surface of the Earth and the other capable of giving higher resolution views comparatively infrequently. Both should carry radar and visible/near infra-red (i.r.) sensors. Operational civilian satellites which are potentially suitable for fulfilling these roles are listed in the table below.

Task	Sensor Types	Number of Satellites Needed	Types of Satellite
Infrequent high resolution monitoring	Visible/near i.r.	One	IRS, JERS, LANDSAT, MOS, SPOT
	Radar	One	ERS, JERS, Radarsat
Frequent lower resolution monitoring	Visible/near i.r.	One	EOS, FY-B, METEOSAT, TIROS-N/NOAA
	Radar	One	ERS?

The study concludes that although operational and planned satellite systems could undertake most of the routine monitoring needed for verification, they would have to be supported by airborne remote sensing. Ground based checks ('ground truthing') would also be needed to check the reliability of remotely sensed data.

Verifying changes in land use

The information required for verification is collected in a three stage process: data acquisition, data collation and data assessment (including independent checking). The study therefore examined problems that might arise at each stage of this process when applied to verifying changes in land use.

Data collection

The main problems likely to be encountered in collecting data about changes in forests by remote sensing are as follows.

i) Detecting selective felling of trees in tropical forest is likely to prove difficult using satellite based instruments. This is not primarily because of the lack of resolution of such instruments but because of the annual leaf fall from trees occurring in such a way that it could be confused with deliberate deforestation. Also, it would be difficult to differentiate between trees that were felled deliberately by mankind and those that died from natural causes. (This problem will occur in monitoring all types of forest.) Airborne instrumentation could discriminate between the two different types of phenomena but it would be extremely costly to use aircraft exclusively for this task.

ii) It would be difficult to measure 'open forests' by satellite based remote sensing and very expensive to do so using airborne instruments.

iii) Cloud cover and other atmospheric phenomena are likely to impede, but not necessarily prevent, forest monitoring by remote sensing. For these and other reasons it is likely to prove necessary to monitor temperate and boreal forests mainly during the summer when it is also easier to discriminate between diseased and healthy trees, certainly in deciduous forests (because they are in leaf). In tropical forests where cloud cover can be semi-permanent, selecting specific times of day at which to monitor is likely to be crucial to obtaining clear images. All types of sites will need monitoring more frequently than would be the case in uniformly fine weather in order to increase the chances of obtaining clear images.

The main problems likely to be encountered in collecting data about changes in agriculture by remote sensing are as follows. (The problems of atmospheric interference can also applies to the agriculture sector.)

i) It is likely to prove impractical to detect animals, and hence count ruminant numbers, by space based remote sensing. Airborne remote sensing using infra-red sensors would generally be preferred for this application but would not be suitable for cases where the animals were 'stabled' or in dense woodland. Counting methods should thus be primarily ground based although it would be cheaper and easier to use airborne sensors for spot checks where appropriate.

ii) The area of rice paddies could be assessed by space based remote sensing. Radar is best suited to the purpose but should be 'backed up' by measurements in the visible/infra-red wavebands.

Both the forest and agriculture sectors need corroboration by data collected by ground based methods. The waste sector and the fertiliser subsector could be monitored more accurately by techniques other than remote sensing.

Data collation

There appear to be no fundamental technical problems associated with collating data from a monitoring regime based on remote sensing. The cost of installing a suitable system could, however, be high.

Data Assessment

In assessing changes in area it will be important to define exactly what constitutes a change. This will be dictated mainly by the accuracy of the data and the type of vegetation under consideration. Also, it will be necessary to decide on how often to measure changes. If there is too long an interval between assessments, small changes that could be easily rectified at an early stage may grow to unacceptable proportions. In addition to defining an appropriate measurement interval, it is also important to set appropriate dates, or at least seasons for monitoring because most living systems change seasonally.

A data assessment system based on digitised layered maps of forests and rice paddies could be accurately georeferenced and could enable rapid, almost unambiguous, comparison of temporally different sets of data. It would, however, be difficult to use data layering methods for counting animal numbers. In this case, straightforward counts from images, or on the ground, would be more appropriate.

Political and economic factors

Any independent regime designed to monitor forest areas and land use by remote sensing will need to possess several features which have important political and economic implications. The major features are listed below.

i) Any independent monitoring regime involving remote sensing should incorporate an agreement that the permission of individual nations would be granted, under acceptable constraints, for any overflights and for the use of any data obtained.

ii) It will be necessary for a monitoring regime to liaise closely with national authorities on how to effect ground based data collection most efficiently.

iii) National polices on forests and land use should take into account the requirements of any monitoring regime and vice versa.

iv) A fair and equitable scheme should be devised for sharing the costs of a independent monitoring regime and for mounting nationally based monitoring efforts.

Conclusions

Any agreement to limit anthropogenic greenhouse gas emissions from forests, rice paddies or ruminants should specify national commitments in terms of vegetated areas (and types) or animal numbers (and types) rather than emissions. This approach would obviate the need for the repeated use of inaccurate emission factors. Emissions from landfill sites could be measured more accurately and relatively efficiently by direct measurement methods and treaty commitments should therefore be in terms of emitted mass of gas. Emissions from fertiliser application should also be specified in terms of mass of emitted gas although in this case the most efficient measurement method would be indirect measurement based on fertiliser production or use.

It would be fairly straightforward to detect changes in areas of dense forest and rice paddies by space based remote sensing using operational or planned satellite systems. It would also be possible to monitor changes in certain types of large ruminant herds by airborne remote sensing methods. Atmospheric interference in the form of cloud is likely to be the most significant inhibiting factor in making such measurements in the visible or infra-red spectra. In many cases, measurements based on the use of microwave radiation are thus likely to be the more effective.

Changes in the areas of open forests and selective tree felling would be very difficult to measure using remote sensing and would probably not be worth monitoring. In the most widespread types of selective felling the trees are not burnt and need not, therefore, be monitored under a regime designed to indirectly measure greenhouse gas emissions.

Currently available data collation and assessment facilities are not sufficiently comprehensive in scope for the task of verification. Fundamentally suitable collation and assessment techniques do, however, exist and suitable facilities could be established without significant research or development effort.

At present, all of the measurements made in the forest, agriculture and waste sectors would be subject to significant error. The main sources of error are inadequate data collection methods and inadequate effort for data collection, collation and assessment. The accuracy of data could be considerably improved by increasing the resources available for gathering, assembling and analysing it.

CONTENTS

Acronyms

AMSU	Advanced Microwave Sounding Unit
ATSR-2	Along Track Scanning Radiometer-2
AVHRR	Advanced Very High Resolution Radiometer
BAHC	Biosphere Aspects of the Hydrological Cycle
CCRS	Canada Centre for Remote Sensing
CDA	Command and Data Acquisition
CEC	Commission of the European Community
CEOS	Committee for Earth Observation Satellites
CEOS	Committee on Earth Observation Satellites
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DIS	Data and Information System
DN	Digital Number
DOMSAT	Domestic Communications Satellite
DVI	Difference Vegetation Index
EDC	EROS Data Center
EOS	Earth Observing System
EPO	Earthnet Programme Office
EROS	Earth Resources Observing Satellite
ERS	European Remote Sensing satellite
ESA	European Space Agency
FAO	Food and Agriculture Organisation
GAC	Global Area Coverage
GAIM	Global Analysis Interpretation and Modelling (IGBP)
GARP	Global Atmospheric Research Programme
GCM	General Circulation Model
GCOS	Global Climate Observing System
GCTE	Global Change and Terrestrial Ecosystems (IGBP)
GIMMS	Global Inventory Monitoring and Modelling Studies
GSFC	Goddard Space Flight Centre
GVI	Global Vegetation Index
HRPT	High Resolution Picture Transmission
HRV	Haute Resolution Visible
ICSU	International Council of Scientific Unions
IFOV	Instantaneous Field of View
IGAC	International Global Atmospheric Project

IGBP	International Geosphere-Biosphere Project
IPB	Interactive Processing Branch
IR (or i.r.)	Infra-Red
ISCCP	International Satellite Cloud Climatology Project
ISLCP	International Satellite Land Surface Climatology Project
JRC	Joint Research Center
LAC	Local Area Coverage
LANDSAT	Land Remote Sensing Satellite
LERTS	Laboratoire d'Etudes et de la Recherche Télédétection Spatiale
LUT	Look-up Table
MERIS	European Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectrometer
MSS	Multispectral Scanner System
MTV	Monitoring Tropical Vegetation
NAS	National Academy of Sciences (USA)
NASA	National Aeronautics and Space Administration (USA)
NCAR	National Centre for Atmospheric Research
NDVI	National Difference Vegetation Index
NESDIS	National Environmental Satellite Data and Information Service (USA)
NIR	Near infra-red
NOAA	National Oceanic and Atmospheric Administration
NPP	Net Primary Productivity
NRC	National Research Council (USA)
SAFISY	Space Agency Forum for the International Space Year
SMMR	Scanning Multifrequency Microwave Radiometer
SOCC	Satellite Operations Control Center
SPOT	Systeme pour l'Observation de la Terre
TM	Thematic Mapper
TOGA	Tropical Oceans and Global Atmosphere programme
TREES	Tropical Ecosystem Environment Observations by Satellite
USGS	United States Geological Survey

1. Introduction

This report examines some of the problems which are likely to arise in verifying treaty commitments to limit anthropogenic emissions of greenhouse gases. It then sets out some solutions to the problems. The report concentrates on issues related to verifying compliance with the Framework Convention Climate Change.

A considerable amount of work has already been done on how to monitor greenhouse gas emissions from the energy sector. Relatively little effort has been devoted either to how the other main emission sectors could be measured or to how compliance with any commitments to limit emissions from these sectors might be verified. This report aims to answer these questions. Specifically, it points out ways of verifying treaty commitments to limit emissions from the forest, agriculture and waste sectors. Most of the emission sources in these sectors could be monitored by remote sensing. Consequently, a large proportion of the report is devoted to an examination of how effective remote sensing methods might be in this application.

The report begins (Section 2) with a general examination of the main types of greenhouse gas emission source in the forest and land use sectors. There is then a discussion of which generic types of measurement method could be used to monitor them in such a way as to enable effective verification of compliance with an international agreement to limit greenhouse gas emissions. Next, the main charactersistics of emission sources in the forest, agriculture and waste sectors are examined in more detail and the relative merits of using direct or indirect measurement methods for their measurement are discussed at some length. It is concluded that, in general, indirect measurement methods would be more effective for verification related monitoring than direct measurement methods. In particular, it is concluded that it would generally be easier, and more accurate, to monitor commitments to emission stabilisation or reduction by monitoring changes in the areas of forests or other types of land use, rather than to try to monitor such commitments directly.

Section 3 of the report is devoted to an examination of the resources available for monitoring forests and other types of land use. The Section concentrates on methods which enable vegetated areas or animal numbers to be assessed. Methods of collecting and collating baseline data are examined first, in outline. Present and future (10 years hence) remote sensing methods are then assessed in detail and the resources available for ground based observations are then examined. The Section concludes with a account of currently available databases on forests and agriculture.

Section 4 of the report examines methods of verifying baseline data. The main issues are examined first and specific details of problems which might arise in the Forests, Agriculture and Waste Sectors are then considered. Finally, general problems which might arise are considered together with methods which might be used to construct a database containing baseline data.

Section 5 examines how to verify compliance with commitments to limit changes to forests or other types of land use (on the assumption that it would be simpler to monitor changes in, say, forest areas that to monitor emissions from them - as discussed in Section 2). The Section deals almost exclusively with how such commitments could be monitored by remote sensing and considers how to solve potential problems in acquiring, collating and assessing data. The Section concludes with a brief discussion of some of the more important political and economic factors that will need to be addressed if this type of monitoring is to be effective.

The Report concludes with a discussion of the more important issues in verifying compliance with commitments to limit emissions from the forest, agriculture and waste sectors. Conclusions are then drawn as to the feasibility of verifying such commitments.

2. Verifying compliance with commitments on forests and land use

In order to verify any treaty commitments designed to limit anthropogenic greenhouse gas emissions from forests or land use it is first necessary to establish means of reliably monitoring compliance with such commitments. This section examines how monitoring might be carried out. It is important to note at the outset that all measurements must yield data on the amount of gas released, not on concentrations. Also, the measurement techniques used and the data collected must enable treaty limited emissions (or human activities giving rise to them) to be monitored at a *national* level - it is nation states that will be the parties to any agreement to limit greenhouse gas emissions and it is therefore the implementation of *national* commitments that must be verified.

To verify that changes in a nation state's greenhouse gas emissions (or activities giving rise to emissions) are in line with its treaty commitments, a comparison needs to be made between two sets of measurements: one which establishes the emissions (or activities giving rise to them) from each signatory nation at the time of an agreement coming into force ('baseline' data) and another which quantifies subsequent emissions or related activities. The two sets of data need to be compiled in a mutually compatible manner, be sufficiently comprehensive and accurate for the task in hand, and be agreed by all of the parties to the agreement.

Under the Climate Convention compliance will be assessed from data contained in 'national reports' which will be compiled by the states which are party to the agreement. Any comparison of different national reports is likely to be invalid or inaccurate without international guidelines and methodologies. Agreed guidelines and methodologies are therefore essential to the effectiveness of any verification regime. However, to build and maintain confidence in the reliability of national reports it is important that they are subject to independent international review. It is also important that data collected by national governments is compared with independently collected data. This report deals primarily with how this independent set of data might be collected.

There are two main methods of measuring greenhouse gas emissions: *direct* and *indirect*. A direct measurement is one in which the mass flow of a given type of gas is measured at its source as, for example, when monitoring the mass of carbon dioxide flowing from a car exhaust. An indirect measurement is one where the mass flow of gas from a source is derived from other, direct, measurements. An example of an indirect measurement is the determination of the mass of carbon dioxide flowing from a car exhaust from data on the fuel consumption of its engine and the proportion of fuel which is converted into carbon dioxide when burnt (the 'emission factor').

Technically, *direct* measurements are to be preferred in any type of monitoring. This is in part simply because they are direct and do not require interpretation but also because they are necessarily more precise and are not subject to errors in calculation, as are indirect measurements. However, many sources in the forests and land use sectors are diffuse and are consequently difficult to measure using conventional mass flow techniques, which tend to be best suited to monitoring continuous flow in confined, well defined spaces such as pipes. Moreover, both these sectors have an extremely large number of sources which means that making direct measurements would involve using a large number of measuring devices (even if monitoring were carried out infrequently). In many situations it is therefore likely to be either technically difficult or expensive to employ direct measurement methods and there is a strong case for relying mostly on *indirect* measurements for monitoring the forest and agriculture sectors.

In this Section the relative merits of using direct and indirect measurement for monitoring the forest and land use sectors are discussed in light of the characteristics of the sources, the potential availability of measurement techniques and, to some extent, their cost. Some of the more important characteristics of the sources, which also have a bearing on how they might be measured, are summarised in Table 1.

In Table 1 the forest, agriculture and waste sectors are divided into subsectors. In the case of forests these subdivisions reflect the two main ways in which trees are cleared: by selective felling (usually within small areas) and by large area deforestation, which is often effected by burning. In the agriculture sector the subsectoral categorisation is rather more straightforward and simply reflects the main anthropogenic sources of emissions. There is only one main source in the Waste sector: landfill. The sector characteristics outlined in Table 1 indicate the nature of the sources in terms of their size, number, continuity of emission, mobility and area.

SECTOR		SECTOR CHARACTERISTICS									
		Source size		Source number		Continuous or intermittent		Static or mobile		Source area point or diffuse	
Sector	Sub-sector	Big	Small	Many	Few	Cont.	Int.	Mob.	Static	Point	Diff.[1]
FORESTS	Clearing	✓			✓		✓	✓			✓
	Selective cutting		✓	✓			✓	✓			✓
AGRI-CULTURE	Rice Paddies		✓	✓			✓		✓		✓
	Ruminants		✓	✓			✓	✓		✓	
	Fertiliser		✓	✓			✓	✓			✓
WASTE	Landfill		✓	✓		✓[2]			✓		✓
	Other		✓	✓		✓			✓	✓	✓

Table 1. Some characteristics of the main emission sources in the forest, agriculture and waste sectors

2.1 Direct Monitoring of Greenhouse Gas Emissions

Direct measurement of emissions entails the detection and determination of the mass flow of a gas from a particular source or sources. To effect such a measurement, all of the emitted gas must evidently be sensed by a measurement device and for this reason it is usually necessary either to confine the gas at some stage of measurement or for the emission source to be in the form of a restricting orifice. Considering the characteristics of the sources in Table 1, many such measurements are likely to be difficult to make, because

[1] A 'diffuse' source is one that emits over a large area.

[2] Assuming a lifetime for landfill emissions of up to 30 years.

most of them are diffuse. Moreover, most are also small, numerous and mobile so that monitoring them would involve making a large number of measurements in many different locations. The main types of measurement problem likely to be encountered in each sector are outlined below.

In the *forest sector* emissions derive mainly from burning or decaying wood, but also from other forms of biomass. The emissions of interest come from burning instigated by mankind and from the decay in trees which are felled or otherwise destroyed by people, as opposed to those which die from natural causes. Some burning of trees is well defined and carried out in ovens or furnaces where emissions are exhausted in such a way that they can be measured (for example, through chimneys). However, most burning is not carried out in a controlled manner; wood is typically either cut from forests and removed to be burnt in small fires elsewhere or it is burnt piecemeal 'in situ'. In neither case can the gases emitted usually be confined sufficiently for them to be measured and it is often difficult to determine where burning is being carried out. Moreover, methane emissions due to decaying vegetation destroyed by mankind are virtually impossible to measure directly.

If *net* emissions are to be assessed, it will be necessary to monitor both the emissions from forests and their capacity to absorb them. Direct measurement of changes in their capacity as sinks is, however, likely to be even more difficult than monitoring emissions. Consequently, it would probably be sensible to only assess emission sources under any agreement to limit emissions. However, the Climate Convention adopts the so-called 'comprehensive approach' where measurement of net emissions from each nation is required. This implies that net emissions from forests may need to be calculated. Estimating net emissions using direct measurement methods is likely to be impossible and would almost certainly be prohibitively expensive. It would also be pointless, because forests absorb emissions from sources other than those from themselves. Any monitoring methods agreed by the Conference of the Parties to the Convention should not therefore aim to monitor *net* emissions from forests.

In the *agriculture sector* there are three main emission sources: rice paddies, enteric fermentation in ruminants and fertilisers. Direct measurement of all of these sources poses problems. Rice paddies are typically of a size which could, in principle, be enclosed for short but representative periods and then be monitored directly. Similarly, it would be technically possible to measure methane emissions from ruminants. However, both types of measurement would be difficult to perform and would be prohibitively costly on the scale on which monitoring would need to be done. (Direct measurements could therefore only be used to provide data for the indirect calculation of emissions.) Nitrous oxide emissions from fertiliser application occurs in small amounts over large areas and are dependant upon prevailing soil, vegetation and weather conditions. It is extremely difficult to measure such emissions under controlled semi-laboratory conditions and it is thus unlikely that reliable direct measurements of overall emissions could be made as part of any generally applicable monitoring scheme.

Landfill sites are potential candidates for direct measurement. They are usually not so large that they cannot be effectively enclosed and the methane drawn off through pipes, thereby enabling measurement of the mass flow of the gas. Indeed, because methane is an efficient fuel, such schemes can be commercially viable. Some small 'waste gas' burning power stations have already been constructed. However, the majority of existing landfill sites do not incorporate systems for either measuring or disposing of gas and it would therefore not be possible to measure emissions directly at present.

From the foregoing discussion it is fairly clear that direct measurement of most of the greenhouse gas emission sources in the forest and agriculture sectors is likely to prove extremely difficult or expensive. The next section therefore considers the prospects for using indirect methods.

2.2 Indirect Monitoring

Indirect measurement of emissions involves calculation from two or more direct measurements of other parameters. The main criterion for selecting an indirect measurement method is that these parameters should be fairly easy to measure accurately. It is also important that the exact relationship between direct and indirect measurements of emissions are well understood and validated. In addition, because errors will inevitably arise during the calculation of emissions from other measurements, it is generally advisable to employ indirect methods of estimating emission which use the minimum number of different types of direct measurement.

Given the problems associated with making direct measurements of emissions from the *forest sector* (mentioned in the previous Section), it would seem more appropriate to consider indirect methods for measuring carbon dioxide and methane emissions caused by anthropogenic activities. For example, if anthropogenically induced changes in forest biomass were known, carbon dioxide emissions could be calculated from 'emission factors' based on data about the proportion of biomass being burnt and the efficiency of burning. However, any emission factor derived from the last two parameters is likely to be highly inaccurate because both parameters would be based on data averaged from a variety of different sources which might be collected in different ways (even if there were agreed sets of guidelines for its collection). Moreover, it would be difficult to measure changes in forest biomass accurately in the first place.

The most practical way of indirectly monitoring emissions due to deforestation would seem to be to monitor the *areas* and *types* of forest instead. This approach has the additional advantage that the capacity of forests to sequester carbon dioxide might be monitored by the same method (as any decrease in forest area would be bound to reduce its capacity as a sink). This task could be undertaken using remote sensing methods but, again, poses the problem of how to estimate emission factors accurately at the stage when commitments to limit emissions are being agreed.

In the *agriculture sector,* the indirect measurement of emissions poses fewer fundamental problems than in the forest sector. Emissions from rice paddies are directly related to plant numbers which are (for a particular plant species and geographical area) related to the *areas* of the paddies. Knowing the magnitude of these areas, the types of rice being grown, and the climate of the region it is possible to establish emission factors from which data on growing areas can be translated into data on emissions. Similarly, it is possible to derive emission factors empirically for different types of ruminants in different geographical regions and to use these factors together with counts of animal numbers to calculate emissions from a particular nation. Nitrous oxide emissions from fertiliser could be estimated from the amount of fertiliser manufactured and the locations in which it is used.

At present, emission factors calculated for the agriculture sector tend to be inaccurate. Much of the data required for such calculations is lacking, as are the systems for collecting it. In principle, these could be developed in the future, allowing increasingly accurate estimates. However, the overall accuracy of indirect calculations is likely to remain low and might pose problems in the reliable verification of national commitments. The accuracy with which nitrous oxide emissions from fertiliser use could be calculated is likely to be particularly poor. Although the quantities of fertiliser produced can be monitored quite accurately (± 10%), the nitrous oxide emissions arising from their use vary considerably depending on local conditions and agricultural practices (± 100%).

As mentioned in the previous section, *landfill sites* are potentially suitable for direct monitoring and, where practical, it would be better to use such methods because they are likely to give more accurate results. Indeed, indirect measurement of landfill sites is likely to prove difficult. To make a reasonably reliable estimation of emissions it would be necessary to know the volume and contents of the landfill, the weather conditions during the measurement period and prior to it, and a number of other factors that could not be established without intensive monitoring.

In summary, most major types of source in the forests and agriculture sectors could be monitored using indirect measurement methods, although landfill sites could probably be monitored better using direct methods. The basic parameters which require measurement are areas (for rice paddies and forests), numbers (for ruminants) and manufacturing production (for fertiliser). In each case an appropriate emission factor has also to be derived to convert the measured parameters into emissions. Inaccuracies can arise in both the measurement of the basic parameters and in the derivation of emission factors. Many of the latter are likely to be subject to significant error for the foreseeable future.

The remainder of this report is devoted to examining, in detail, how to measure the basic parameters of forest and agriculture areas and animal numbers accurately using remote sensing. The determination of emission factors is also considered but in less detail. This is because the authors believe that the emphasis should be on drafting agreements which, to a large extent, eliminate the need for emission factors. This type of approach is outlined in the following subsection.

2.3 Monitoring Commitments to Regulate Forest and Land Use Areas

The main criterion for selecting an indirect measurement method is that the directly measured parameters from which it is derived should be fairly easy to measure using direct methods. It is nearly always possible to make direct measurements of parameters such as forest areas or animal numbers. It may be difficult to make such measurements accurately, but they can usually be made. It is not usually possible, however, to derive the related emission factors accurately. They are nearly always subject to error because (certainly in the forest and agriculture sectors) they comprise averaged data which is often calculated from other averaged data. (For example, any sort of emission factor used for calculating emissions due to forest burning from data on forest areas will be derived by taking the mean of the means of sets of data on the biomass of trees, the efficiency with which they might burn and the probability of their being burnt.) Consequently, the use of emission factors will always introduce inaccuracies into any indirect measurement and, in the case of the measurements being investigated here, such errors are likely to be large.

In principle, verification of the effective implementation of an agreement to limit emissions will not be impaired by the use of inaccurate emission factors, as long as they are universally applied and the errors to which they give rise are thus systematic. However, this is unlikely to be the case in practice. Emission factors are likely to be changed in line with the latest scientific thinking or technical progress on a particular topic. Verification procedures based on contestable and changing methodologies are likely to undermine compliance and prove ineffective. The simplest way around this problem is to avoid the use of emission factors completely and to specify treaty commitments in terms of the parameters which can be measured directly. In this case, these parameters would be forest and agricultural areas and animal numbers.

The main problem with employing this approach is that in order to negotiate an agreement to preserve forests and limit agricultural areas or animal numbers, rather than the emissions from them, it would still be necessary to make use of emission factors. Otherwise, nations could not be sure that their new set of commitments bore any relationship to their primary goal to limit emissions. Neither could they be sure that emission factors would not need to be revised in the light of scientific and technical progress, as mentioned above. This difficulty could be overcome by ensuring that any agreement specified that the validity of emission factors (together with their associated commitments to preserving forest areas, etc.) was reviewed periodically.

The main advantage of this approach is that it would enable verification of compliance to be assessed to a greater degree of precision than if emissions were measured. Compliance with commitments to limit areas and numbers could, of course, always be correlated with primary commitments to stabilise or reduce emissions. Moreover, this could be done using only one set of agreed emission factors, thereby avoiding the introduction of systematic errors.

Given the suitability to verification of the area and number measurement approach, much of the remainder of this report is devoted to detailing how to make such measurements, primarily by remote sensing.

3. Resources for monitoring forests and land use

This Section examines resources which are, or could be, available for monitoring greenhouse gas sources now or in the immediate future. The emphasis is on the use of remote sensing methods for monitoring land use characteristics, in general, and *vegetated areas* and *animal numbers* in particular, as outlined in Subsection 2.3. There is comparatively little discussion of how to monitor nitrous oxide emissions from fertiliser or methane emissions from landfill sites. This is primarily because remote sensing is probably not an appropriate technique for monitoring either type of source. The best way to measure emissions from fertiliser would probably be by indirect methods based on fertiliser production statistics. Emissions from landfill should probably be measured directly.

The Section begins with a discussion of the component parts needed to set up an effective verification related monitoring regime. There then follows a detailed account of satellite based remote sensing systems and a relatively brief examination of airborne remote sensing systems. Resources for ground observations are then examined and, finally, an outline description is given of current database resources.

3.1 Components of an Effective Monitoring Regime

In the previous section it was mentioned that any effective monitoring regime would need to employ at least two separate data collection systems - one for establishing conditions prevailing at the time of an agreement coming into force (i.e. 'baseline data') and another to measure subsequent changes to these conditions. There may be an additional requirement for a third system of measurements specifically designed for the purposes of independent verification, particularly in monitoring agreements such as the Climate Convention where all of the data would otherwise be collected by national governments (and consequently run the risk of being suspected or disputed by other governments).

This subsection briefly examines the basic components which any verification related monitoring system must have in order to measure changes in the agriculture and forest sectors. There are a number of different ways of obtaining data from these sectors. Methods of collecting baseline data are outlined first. Methods of monitoring changes in the forest and agriculture sectors are then discussed. These concentrate on monitoring methods based on remote sensing techniques, which offer the best prospects for routine verification related monitoring of vegetated areas and animal numbers.

3.1.1 Baseline Data and Statistics

The reliability of any monitoring system designed to measure changes is absolutely dependant on the accuracy and reliability of the baseline data from which the changes are measured. As complete and accurate a record as possible is thus required, preferably containing information from a variety of sources in a variety of different forms (i.e. photographic, numeric, etc.). The data should be catalogued in a simple, easily accessible way and should be sufficiently complete to enable all possible changes to be measured from it. An additional important feature of any such system is that it should, ideally, be capable of distinguishing between naturally occurring and anthropogenic changes.

Baseline data on forest and agricultural areas and animal numbers is available in several forms. Most governments, certainly those of developed countries, keep generalised data about different kinds of ground cover in the form of maps. They also typically maintain detailed numerical information on crops and animal numbers, and in many cases, on forest types and densities. In addition, databases of remotely sensed information on most types of vegetation are increasingly available. All such information could and should be compiled and collated in order to form a comprehensive baseline of data for each nation participating in an agreement to limit emissions from the forest and agriculture sectors. (It is worth noting that there is far more information about the areas and numbers of sources in these sectors than there is about emissions from them. The greater comprehensivity of the baseline data is yet another reason for selecting this approach to verification related monitoring instead of attempting to measure emissions directly.)

Different types of information comprising the baseline data are typically kept separately from each other, although some recently developed methods allow different types of information to be stored in 'layers' which can be compiled into more complex composite layers. In one such system called a Geographic Information System (GIS) several layers can be compiled into one composite layer while still retaining the individual characteristics of each component layer. Data can be added to or subtracted from individual layers at any time in order to generate a more complete or up to date data set.

Several large databases which contain information necessary for compiling a worldwide set of baseline data of the type required already exist. The United Nations Environment Programme (UNEP), the Food and Agriculture Organisation (FAO) and the World Resources Institute (WRI), for example, all possess a considerable amount of data on forest areas, although it should be emphasised that their existing databases are far from complete. A database designed for the task under consideration here would at least need to attempt to be comprehensive. In many instances, the data would also need to be more accurate than that currently available.

It cannot be emphasised too strongly that baseline data collection is a singular and fundamentally important task. Repetition of the task may not be possible without amending previously agreed treaty commitments and all subsequent monitoring will be dependant on the reliability of the baseline data.

3.1.2 Monitoring Techniques: Sensors and Platforms

This subsection discusses the two main parameters which need to be measured by remote sensing under a regime designed to monitor the forest and agriculture sectors: land use areas and animal numbers. (Nitrous oxide emissions from fertiliser and methane emissions from landfill would, as mentioned previously, be better measured by other methods.)

Parameters relating to vegetation are generally measured by *sensors* which are sensitive to either visible or infra-red electromagnetic wavelengths, or both, because plant foliage exhibits strong, characteristic absorption and reflection in these bands (see Appendix 1). By measuring the intensity of emissions from vegetation at several of these wavelengths it is often possible to sense not only the type of plants present but also their condition (for example, whether or not they are diseased). It is also possible to monitor vegetation with certain types of radar which enables the presence or absence of particular classes of plant (trees, grass etc.) to be detected by differences in their 'surface roughness'. Animals can be located by similar methods to those used for vegetation, infra-red sensors being particularly good for detecting their presence from thermal emissions due to their body heat.

Apart from selecting sensors which operate in appropriate spectral bands for the detection of vegetation or animals, it is also necessary to select sensors with an appropriate spatial resolution. High resolution sensors might seem appropriate for all applications but, because remote sensing at high resolutions tends to limit the size of scene that can be observed and gives rise to very large amounts of data, it is often more appropriate to use the minimum resolution possible for any particular application.

Two main types of *platforms* for carrying sensors are available for remote sensing: satellites and aircraft. Satellites have the advantage of being able to cover large areas in a fairly short space of time. The main advantage of aircraft, and particularly helicopters, is that they can visit and remain at a specific location to carry out higher resolution inspections. There is consequently likely to be a role for both satellites and aircraft in any monitoring regime: satellites for regular, frequent, broad area observation on a global scale and aircraft for high resolution checks on areas where non-compliance with an agreement is suspected.

Data collected by satellite based remote sensing systems evidently needs to be transmitted to ground receiving stations for further processing and analysis. Thus, in addition to sensors and platforms to carry them, any monitoring regime will also need receiving stations, data processing facilities and data storage capacity.

Ground based data collection is important to supplement and validate remotely sensed data. Data acquired from satellites or aircraft has at some stage to be validated by 'ground truthing' missions.

3.1.3 Measurable Changes

The primary task of any remote sensing system for monitoring the forest and agriculture sectors will be to monitor changes in vegetated areas and animal numbers. However, to perform this task effectively a large number of other anthropogenic and naturally occurring features will also need to be taken into account. There are too many such features to detail in this short section. Some typical factors which will need to be taken into account in the forest sector are therefore outlined below as an example.

In the forest sector it is necessary to first closely define the limits of the forest area under investigation. Within the broad band category of forest area, finer details concerning the forest composition in terms of the density and species of trees will be required. Any reforestation activities will also have to be taken into account as these will probably offset against any deforestation activities for the purposes of commitments made under the Climate Change Convention.

Reforestation can take two forms: natural (self-setting) and deliberate (replanting). As regrowth follows a distinct pattern of 'succession' from small bushes to larger shrubs and trees, many different types of vegetation will have to be taken into account. Deliberate deforestation could be assessed by monitoring the development of roads and other activities associated with the logging industry such as sawmills.

A fundamental problem associated with monitoring forest areas is deciding on the definition of a forest. When does a group of trees constitute a forest and how close together do the trees have to be? Careful classification of different types of forest is evidently essential for effective monitoring (see Appendix 3). Accurate assessment of the condition of trees is also likely to be important, particularly if their ability to sequestrate carbon dioxide is to be taken into account.

3.2 Space Based Remote Sensing Capabilities

Satellite based remote sensing systems have several advantages over other types of monitoring system used in verification. They can, for example, pass unhindered over national boundaries and, in principle, provide data of uniform quality to all parties to an international agreement. In the particular case of a convention intended to regulate forests or land use, they offer the additional potential advantages of being able to provide both detailed and broad area information about the type, condition and extent of vegetation. Satellite based systems generally lack the discrimination required to detect animals, such as ruminants, and this application is not therefore discussed here. (Such sources are discussed in the following subsection on airborne remote sensing.)

Four main tasks were involved in selecting remote sensing systems for verification related monitoring of forests and land use. The first was to decide which characteristics of forests and other foliated areas would need to be measured in order to allow changes in them to be detected. The second was to establish the set of spatial, temporal and spectral measurement systems available on operational and planned satellites. The next was to examine modes of data acquisition and distribution from satellites. Finally data processing requirements were investigated. The characteristics of forests and land use which will need to be measured to enable effective verification were considered in detail, as were the characteristics of satellite systems. The other two factors were considered in outline here, but in greater detail in Section 3.5.

This study concentrates on satellite based remote sensing systems which are, or are planned to be, operational over significant periods of time (more than about two years) and from which data are likely to be routinely available. Experimental systems are not considered, except where definite plans exist to incorporate them in future operational missions. Military satellite systems were not investigated in detail and are not reported here, because of the lack of specific information on their performance and also because data are unlikely to be available from them on a regular basis.

This subsection of the report is divided into three main parts. The first part outlines those parameters relating to forests and land use which will need to be measured for effective verification. There is then a detailed description of those satellites and their systems which could realistically be used for monitoring changes in the areas of forests or other vegetation. Finally, conclusions are drawn on the effectiveness of satellite based remote sensing for monitoring changes in forest areas and land use. For those not conversant with satellite based remote sensing systems, an introductory section on this topic is included in Appendix 1.

3.2.1 The Role of Satellites

In addition to their potential as a means of measuring forest and land use areas, satellite borne sensors have several fundamental advantages over other monitoring methods which might be used in a verification regime.

1. Satellites are, or can be, independent of restrictions due to national sovereignty. They can cross borders unheeded and are difficult to 'blind' or destroy.

2. Satellite borne remote sensors are capable of providing both broad area and detailed information.

3. Satellite based remote sensing could provide all signatory nations to the Convention with information of uniform quality.

4. Satellites could be independently controlled by an internationally based verification body.

There is thus a strong case for employing satellite based remote sensing in any verification regime for which the technique is technically well suited. For the technique to be suitable for measuring changes in vegetated areas under the Climate Convention the main system requirements given below must be fulfilled.

3.2.2 System Requirements

Any monitoring system must fulfil the five main criteria listed below in order to detect changes in forest areas or land use successfully.

i) The monitoring system must be able to discriminate between different types of vegetation, and between them and other sorts of land cover (or water or bare land).

ii) The system must be able to measure the total area of vegetation on a specified site. Area measurement can be considered as taking two distinct forms. Firstly, it is necessary for the system to be capable of assessing the overall area of a site within a given perimeter. Secondly, it must be able to measure any clearing or other changes within the perimeter. The second measurement or measurements can then be subtracted from the first to give the total area.

iii) The monitoring system should enable a very large number of sites to be checked for changes at regular intervals and or, in some cases, continuously. The system should not, therefore, be prone to failure.

iv) The system must enable the precise geographical location of all observed sites and images to be determined repeatably.

v) Information from the measuring system should become available rapidly and in an easily understandable and unambiguous format.

The ramifications of these requirements for any remote sensing system are now given under the main headings identified above.

3.2.2.1 Discrimination

Ideally, the smallest outline that should be detectable by a remote sensing system designed for monitoring vegetation is an individual plant. To detect individual trees a sensor with a spatial resolution of the order of one metre would be thus be necessary. In practice, however, there is little need to detect individual trees or other forms of vegetation but only any changes in areas of vegetation. The resolution required to undertake this task varies with the type of forest or land use under consideration. For example, for assessing dense forest a resolution of the order of 10 metres would be adequate in most cases, but for other applications a higher degree of resolution may be needed.

An important factor in establishing the resolution of any observing system is deciding how to process all of the data that will be generated if a high resolution system is routinely used for global monitoring. The World's forests and agricultural production regions cover an area of more than one hundred million square kilometres. Monitoring such an area at a resolution of one metre would generate an immense amount of data which would require vast resources to process.

On balance, taking into account possible data handling problems, currently available satellite systems, and the resolution needed to monitor areas to an accuracy of about one percent, a spatial resolution of the order of ten metres would probably be appropriate for a space based remote sensing system designed to monitor most changes in area. Such a system could certainly detect (if not measure) most changes to dense forest or woodland. It would be particularly effective if supported by an airborne remote sensing system for high resolution examination of areas detected as changing by the satellite borne system.

There are several satellite systems which have sensors with spatial resolutions in the range 10 to 50 metres. Some, such as the Landsat 'Thematic Mapper', operate in the visible and near infra-red spectra. Others, such as ERS, have microwave radars. These visible/near infra-red and synthetic aperture radar (SAR) systems can discriminate between different densities and species of vegetation. At a resolution of tens of metres any particular picture element (pixel) does, of course, typically contain information about more than one species of plant. However, averaged intensity information from a particular group of plants can often be distinguished from a dissimilar group. For example, in the case of visible or infra-red sensors, the reflection and absorption characteristics of closed canopy forest is dissimilar from grassland or scrub.

Indeed, different types of forest or agricultural activities can be easily distinguished, given sufficiently high quality data. Similar distinctions can be made between the surface roughness of different vegetation using SAR. Also, particularly using radar, boundaries between different types of vegetation can often be further enhanced by viewing at a high off nadir angle to increase shadowing effects.

Overall, a resolution of between ten and fifty metres is adequate for discriminating those changes in forest and land use areas likely to be of interest to a verification regime, assuming that accurate geographical registration can be obtained between different images. Atmospheric water vapour and, in particular, cloud is likely to be the most important limiting factor in preventing this resolution being achieved for measuring forests and rice paddies. This is because many paddies and forests, particularly rain forests, are usually at least partially covered by cloud. Radars are thus likely to be essential in addition to visible/i.r. systems because of their ability to penetrate cloud cover.

3.2.2.2 Area Measurement

The accuracy with which the area of a site can be measured depends primarily on the spatial resolution of the sensor system used to measure it. In the case of civilian satellite borne sensor systems, this can be as high as ten metres. For monitoring large areas (more than one kilometre square) this represents a possible error of less than one percent, assuming that the area of a site is determined from the dimensions of its perimeter. This degree of accuracy would be adequate for most verification purposes. On the other hand, localised clearances or changes in vegetation of less than ten metres average dimension would not be measurable, although they might be detected from changes in absorption or reflection. Selective felling of individual trees would thus be impossible to measure even if it were detectable, unless recourse to airborne or ground based systems was possible.

In practice, the inability to measure selective changes to small areas of vegetation is unlikely to be a severe problem when using high resolution sensors (10 to 50 m). To avoid detection by such sensors vegetation would need to vary in separate, isolated patches at some distance from each other, otherwise the reflection/absorption spectra or the surface roughness values of the area would change significantly. Such changes are trivial in terms of overall land use and, in any case, man-made changes in vegetation do not normally occur in this way. For example, in logging it is necessary to have access to felled trees in order to remove them and this means removing swaths of forest which could be detected. Similarly, groups of small clearings made for agricultural purposes tend to be fairly close together or linked by access roads and would thus be detectable and, probably, measurable.

3.2.2.3 Comprehensivity and Reliability

Any system designed to monitor changes in forest cover or land use will necessarily need to be global in scope and be capable of assessing a large number of sites. If such an assessment were performed daily at a resolution of ten metres it would be a formidable task. However, most changes in forests and land use occur fairly slowly and there is consequently little requirement for frequent monitoring using high resolution sensors - once or twice each year would be adequate for most purposes. Those changes which do occur rapidly also tend to do so on a large scale and can therefore be detected by fairly low resolution instruments. (Most forest or brush fires of significance can be detected, for example, from their smoke plumes, using images from meteorological satellites with sensors with a resolution of about 1 km.) A monitoring system giving comprehensive (global) coverage with a manageable amount of data would therefore comprise both high and low resolution sensors - the former giving data infrequently and the latter frequently.

The reliability of most satellite borne sensor systems is good, but sensors can and do fail. Given the extremely long timescales needed to prepare new satellites, it is desirable that any system used for verification is fully backed up.

3.2.2.4 Registration

Precise geographical registration of images acquired from space borne sensors is essential in any work requiring the detection of small changes in area. Good digital processing systems for providing suitable georeferenced data already exist, although they could be improved.

3.2.2.5 Data availability and interpretation

Most data from sensors on board satellites is, or can be, transmitted to ground receiving stations within a short period of it being collected. Any delays in receiving data are thus likely to be due to problems associated with errors in the information or to hold-ups in data processing or handling. Assuming adequate computing and storage facilities, processing and handling of images required for verification should be relatively straightforward because most are, of necessity, highly repetitive and need to be in a standard format or formats. There should thus be few delays in the availability of data, other than those caused by system malfunctions or lack of data processing power.

Data interpretation for detecting changes in vegetation basically involves comparing images of the same area. If the images are clear, then this involves comparing successive pictures and identifying any changes in spectral intensity or areas of particular features. Suitable automated routines for performing such tasks already exist, although they could undoubtedly be developed further.

3.2.2.6 Summary of Requirements: Specification

From the foregoing discussion it would appear that a space based remote sensing system designed to measure changes in forest areas or land use should include the characteristics and components summarised below.

The system or systems should either carry sensors operating in combinations of the visible and near infra-red wavebands which enable discrimination between different types of vegetation or should carry sophisticated microwave radar, such as SAR. In the case of instruments operating in the visible and infra-red bands the spectral resolution of the sensors should ideally be at least seven bits. For optimum viewing capability under as many conditions as possible, both visible/i.r. and radar should be included in any overall system.

The maximum spatial resolution of the system as a whole should be of the order of ten metres both for visible/i.r. and radar sensors. The system should be capable of observing any site on Earth at a resolution of the order of ten metres and at a frequency of about once per year, in order to enable changes in vegetation area or type to be assessed in detail. (The exact frequency of such observations will depend on the nature of agreed implementation review procedures). The high resolution observation capability should also be available at relatively short notice (days) in order to carry out spot checks on particular sites. An even higher resolution capability, probably airborne, should also be available for detailed inspection.

In addition to the high spatial resolution system, a lower resolution system capable of frequent, possibly daily, views of any particular area is required. The resolution of this system needs only be about 1 km and it would detect fairly large area, rapidly occurring, phenomena, such as forest burning. The low resolution system should, ideally, include visible/i.r. and radar based sensors.

A global network of ground receiving stations would be required to take data from the satellite borne sensor system. At least one large data handling, processing and distribution centre would be needed. All ground and satellite based systems would need to be fully backed up.

3.2.3 Suitable Operational and Planned Satellite Systems

This section is to examines the existing and planned satellite systems which might be suitable for fulfilling the basic monitoring requirements of a space based remote sensing system for verifying compliance with an agreement to preserve forest areas or restrict land use. The aim is to give some idea of the feasibility of using currently available systems for the task rather than be comprehensive. (Although this examination is made with the Climate Convention in mind such a system could equally well be suited to verifying compliance with an agreement on forest conservation or desertification.)

Most operational and planned satellite systems which can be used for earth observation are listed in Table 2, together with some of the characteristics of their sensors which are relevant to this application. (Military and experimental systems are not included, mainly because they are unlikely to be continuously available for sufficiently long periods.)

Satellite Programme	Type of Orbit	Sensor Types of Interest	Spatial Resolution	Temporal Repetitivity
EOS (USA) 6 planned 1998-	Polar	Visible/near i.r., and microwave radar	0.5 to 1 km	Unknown (days?)
ERS (Europe) 1 operational 1 planned 1994-	Polar	Microwave radar (SAR)	26 m	3 days
FY-B (China) 1 operational	Polar	Visible/near i.r.	1.1 to 5 km	1.75 hours
GMS (Japan) 1 operational 2 planned 1993-	Geostationary	Visible/i.r. (no near i.r.)	1 to 8 km	30 minutes
GOES (USA) 1 operational 5 planned 1992-6	Geostationary	Visible/i.r. (no near i.r.)	1 to 14 km	30 minutes
GOMS (Russia) 3 planned 1992-	Geostationary	Visible/i.r. (no near i.r.)	1.25 to 6.35 km	1 hour
IRS (India) 2 operational 2 planned 1994-6	Polar	Visible/near i.r.	72.5 x 36.5 m 10 m planned	22 days
JERS (Japan) 1 operational	Polar	Visible/near i.r. and microwave radar (SAR)	18 x 24 m (18 x 18 SAR)	44 days

Table 2. Summary of Operational and Planned Earth Observation Satellites (continued on next page).

Satellite Programme	Type of Orbit	Sensor Types of Interest	Spatial Resolution	Temporal Repetitivity
LANDSAT (USA) 2 operational 2 planned 1993-7	Polar	Visible/near i.r.	56 x 79 m (30 x30 m planned)	18 days 16 days planned
METEOSAT (Europe) 4 operational 1 planned 1993 and more after 1998	Geostationary	Visible/near i.r.	2.5 to 5 km	30 minutes
MOS (Japan) 2 operational	Polar	Visible/near i.r.	50 x 50 m	14 days
NOAA/TIROS (USA) 6 operational 3 planned 1994-8?	Polar	Visible/near i.r.	1 to 4 km	12 hours
Radarsat (Canada) 1 planned 1994	Polar	Microwave radar (SAR)	30 m (10 x 10 SAR)	24 days
SIR-C/X-SAR (USA) Shuttle flights 1993-6	Approx. polar	Microwave radars	25 to 40 m	Unknown
SPOT (France) 2 operational 3 planned 1993-9	Polar	Visible/near i.r.	20 x 20 m	26 days

Table 2. Summary of Operational and Planned Earth Observation Satellites (continued from previous page).

It may be seen from Table 2 (and from the complete versions of the Table in Appendix 2) that the obvious candidates for the low resolution, high frequency monitoring task mentioned in the previous section seem to be the geostationary satellites. Many carry sensors which are sensitive to visible radiation and, in most cases, the spatial resolution of these instruments is in the range 1 to 2.5 km. They are thus fundamentally well suited to the task under consideration. However, only one programme, Meteosat, has sensors which function in the near infra-red waveband. Meteosat is also the only programme with sufficient satellites to give even reasonably global coverage at a low resolution but fairly high frequency. Moreover, none of the satellites has a radar capability of the type required. None of the programmes is thus ideal for the task of monitoring changes in forest areas and land use on a routine, frequent, basis. (The geostationary satellites listed were designed primarily for meteorological applications and so this conclusion is perhaps not surprising.)

Most of the polar orbiting satellites listed in Table 2 were designed for earth observation and thus carry either visible/near i.r. sensors or radars. Indeed, the Japanese Earth Resources Satellite (JERS) carries both and so may the planned EOS programme. The spatial resolution of most of the sensor systems is between ten and fifty metres and is thus adequate for sensing most changes in forest areas and land use within the criteria laid down previously. The resolution of the operational and planned advanced TIROS-N/NOAA satellite series and the planned EOS series is significantly less high than the other satellites at about one kilometre. However, as satellites from both of these series have a short temporal repetitivity they could be used for the high frequency, low resolution function in the visible/near i.r.

In principle, most of the requirements of a monitoring system to detect changes in forest areas and land use could be met using existing or planned satellite systems (given that this is supported by an airborne remote sensing system for very high resolution measurements). The EOS and TYROS-N programmes could meet most of the requirements for fairly low resolution, frequent measurements in the visible/near i.r. and most of the other polar orbiting satellites could meet the higher resolution requirements. The ERS satellite could, to quite a large extent, meet the need for a frequent radar sensing capability. The satellites which could, theoretically, be used in a monitoring system, together with their roles in such a system, are outlined in Table 3. (It should be emphasised that this is not intended to be a definitive system.)

Task	Sensor Types	Number of Satellites Needed	Types of Satellite
Infrequent high resolution monitoring	Visible/near i.r. Radar	One One	IRS, JERS, LANDSAT, MOS, SPOT ERS, JERS, Radarsat
Frequent lower resolution monitoring	Visible/near i.r. Radar	One One	EOS, FY-B, METEOSAT, TIROS-N/NOAA ERS?

Table 3. Some Potentially Suitable Operational and Planned Systems.

In conclusion it would appear that operational and planned satellite systems could be used for monitoring forest areas and land use in a regime designed to verify compliance with the Climate Convention.

3.3 Aircraft Based Remote Sensing Capabilities[3]

In a verification regime designed to monitor changes in forest or agricultural areas or animal numbers, airborne remote sensing offers basically similar capabilities to satellite borne systems but at a higher resolution.

The main advantages of using airborne remote sensing systems are that they can yield much higher resolution and more detailed images than satellite based systems, simply because they are nearer to the ground. They can also give a far wider range of information than satellite borne systems because aircraft can carry a wider range of larger sensors. Indeed, because aircraft can reload relatively easily compared to spacecraft and can carry large payloads, they offer the prospect of being able to observe almost any type of phenomena occurring on the ground in detail. In addition, aircraft can be directed towards almost any site at short notice, whereas satellites cannot. Indeed the range of capabilities of airborne sensor systems is considerable and far greater than those of space based systems.

3 The word aircraft is used here in its generic sense to include both fixed wing and other types of craft, such as helicopters.

The main disadvantage of using airborne rather than satellite borne remote sensing systems is that the size of the scene which they can examine is limited by their comparatively low altitude. Also, the cost of acquiring data from a particular area is often higher - in large part because the capital cost of satellites is usually written off and their operational costs are quite low, whereas this is not normally the case for aircraft.

The limited scene size available from airborne systems, together with their fairly high cost, make it impractical to employ them for monitoring the entire surface of the Earth on a routine basis, as can satellite borne systems. In any regime intended to monitor forest or agricultural areas they are thus likely to act in a support role for satellite based systems. Space based sensors would be used for routine monitoring and aircraft based systems would be used to check on suspected 'trouble spots' identified by the spacecraft (as outlined in the previous Section).

Airborne remote sensing systems have a potentially valuable role in counting or at least checking on animal numbers. The limited spatial resolution of the sensor systems on Earth observation satellites renders them ineffective in this application. Many airborne systems can, on the other hand, detect the larger ruminants fairly easily. The accuracy with which they could be used to count animal numbers depends mainly on the amount of cover available to obscure the animals. The larger ruminants such as cattle which typically graze in open areas could probably be counted with reasonable accuracy, especially if infra-red sensors were used to detect the thermal 'fingerprint' of animals partially hidden by trees. Such methods would certainly be useful in spot checking data on herd sizes obtained by other means.

Aircraft are particularly suitable for carrying LIDAR systems which can give an accurate profile of trees in forests.

Many aircraft and airborne systems are potentially suitable for monitoring and it would be a technically fairly simple to convert aircraft for the task. The main limitation on how many airborne systems could be employed for verification related monitoring would be cost. Setting up data collection and collation systems might also pose problems, because most airborne instrumentation does not yield data in a format that would be compatible with that gathered from satellites. This sort of problem is not, however, likely to prove technically insuperable.

3.4 Resources for Ground Observations

'Ground truthing' is performed in order to check the validity of data gathered by other methods. It is particularly important for checking on data collected by satellite based remote sensing systems, where information is typically acquired at spatial resolutions which are insufficient to pick out individual components of the forest and agriculture sectors, such as trees.

Ground truthing should not be viewed as a 'poor man's' version of satellite photography. It can, and should, supply information that cannot be gathered in any other way. In terms of resolution, it is always of higher quality than remotely sensed data because it is gathered at much closer quarters. In the forest sector, for example, ground truthing has the advantage over remote sensing of enabling trees to be viewed from below, rather than above, which allows far more data to be obtained about the physical characteristics of the vegetation. Ground truthing should thus be seen as a exercise that enhances the remotely sensed data as well as validating it.

Ground truthing usually has to be done on a local scale, rather than being globally organised as in the case of space-based remotely sensed data collection. The task will thus tend to fall to individual nation states and their local authorities. Ground truthing will probably be carried out as part of national surveys, with the developed countries using it as a check on remotely-sensed data and developing nations probably making it their main method of data compilation. It will probably not be the responsibility of an international agency although, if verification is to be performed effectively, an independent ground truthing operation run by an independent body such as the United Nations should be considered. (This role could, for example, be fulfilled by the armed forces of nations operating under UN supervision.)

Little technical equipment is needed for ground truthing, the main requirements being manpower and access to sites. The number of sites monitored affects data quality - the greater the number of sites the greater the accuracy of the data. Also, careful selection of monitoring sites is essential in order to obtain representative data. In a medium sized country such as the UK the number of sites deemed reasonable for ground truthing in the forest sector would probably be about 100, the number currently used by the UK Forestry Commission.

Usually, the resources for some sort of ground truthing will already exist within most nations. Some international datasets also exist. For example, the UNEP sponsored GRID/GEMS database has a dataset collected by NASA of vegetation in Ghana which is made up of AVHRR photographs taken at a resolution of about 1 km. These were validated in a ground truthing exercise that entailed monitoring 100 pre-determined sites.

3.5 Database Resources

In general, databases containing information on agriculture are more comprehensive than those containing information on forests, because most nations consider data on their agricultural activities to be of primary importance for government, whereas details on forests are often considered to be less important to governments. Because of this discrepancy this section is divided into two parts: one on the forest sector and one on the agriculture sector.

3.5.1 Databases on Forests

Most countries that have considerable expanses of forest will have already carried out surveys of their own and will have, at least, rudimentary databases. The quality of these national databases will obviously depend upon the resources of the country in question and the importance it attaches to its forests. The northern boreal forests and the temperate forests in Europe and North America tend to be well documented. The great tropical forests of the world, centred around the equator, are mostly in developing countries, which generally have limited resources from which to finance national surveys. There is thus a wide range of databases of different sizes and completeness. Rather than attempt to list all of these, a few typical examples of different types of inventory are outlined below.

3.5.1.1 National Inventories

In the UK, inventories are compiled by the Forestry Commission. Each year an assessment of the nation's forests is made by a combination of aerial photography and ground-based monitoring of about one hundred representative sites. Five species are catalogued in terms of their general health at the one hundred sites. As shown in Appendix 5, the survey is quite extensive and is designed to give a representative picture of the nation's forests. The data collected forms both the national dataset and that which is forwarded to the international databases such as one run by FAO/UNEP.

The UK national assessment follows a systematic procedure involving the assessment of indices relating to tree growth rates (the density of the crown, circumference of the trunk etc.) and general health for each species under inspection. Designated plots of tree stands for each species are monitored from the ground, their distribution being such that a complete national picture is obtained. Aerial photography of the tree stands is used to corroborate ground monitoring, usually using black/white film at a scale of 1:10,000. Examples of this type of practice are shown in Appendix 6.

An example of a national database in the developing world is that run by Brazil. The National Space Agency (INPE) is responsible for the acquisition, processing and storage of remotely sensed data of the country's rain forests. The data is collected by AVHRR sensors and has a spatial resolution of 1 km. Many of the larger developing countries, such as India and China, have their own satellites and ground-receiving stations and the ability to store data. (Appendix 4 details the extent of such facilities worldwide.)

3.5.1.2 Regional Inventories

There are, as yet, few regional inventories on forests although one fairly comprehensive one is being developed by the European Community. The European Commission (Directorate General XI) is responsible for a regional database called CORINE. The original idea behind this database was to collate data from national databases in Europe concerning the state of the environment and its natural resources, with the further intention of enhancing information exchange. A number of specific datasets were highlighted as being of particular significance (biotypes of importance for nature conservation, acid deposition and its effects on soils etc.). Altogether CORINE comprises some 40 sub-projects (an overview being given in Appendix 7). Of relevance to forestry are the datasets covering Natural Potential Vegetation and Land Cover. CORINE is planned to expand, if and when the European Environmental Agency becomes operational. CORINE will then be renamed as the European Environment Monitoring and Information Network (EEMIN).

The CORINE and related databases are run using the Geographic Information Systems (GIS) technology.

3.5.1.3 International Inventories

The main agencies responsible for the co-ordination of forestry-related data are the United Nations Environment Programme (UNEP) and the United Nations Food and Agriculture Organisation (FAO). The latter takes the lead role in collecting the raw data[4]. The combined data is presented in the UN Environmental Report (edition 1), published in 1987. The data cover some 76 countries and are represented as either 'Open Woodland' or 'Closed Forest' . In addition, data on both deforestation and reforestation are given.

The FAO/UNEP data are used by the GRID/GEMS database operated by UNEP, principally in Nairobi but also at other regional offices. Data on forest cover are fed into the GRID system (Geographic Resource Information Database) along with many other 'layers' of data (such as that on soil types, population, water and air quality) so that a multi-layer database is formed. Then, by superimposing these separate layers of data, a composite picture of the environment at a specific geo-referenced position is derived. This can be used to elucidate the causes of environmental damage, such as the causes of an increase in deforestation at a particular location. The system is primarily a tool for use by development

4 For details of the classification system used by the FAO, see Appendix 7.

agencies. It is of less relevance to monitoring of greenhouse gas emissions brought about by deforestation activities.

An outline of the GRID/GEMS system is given, schematically, in Appendix 8.

The World Resources Institute (WRI) publishes tables of deforestation rates for most forested countries of the world, but all of its data originates from FAO/UNEP.

3.5.1.4 Monitoring Agencies

Bodies that measure forests and land use (invariably by remote sensing), include:-

1. Goddard Institute for Space Studies, USA,
2. National Oceanic and Atmospheric Administration (NOAA), USA,
3. National Aeronautical Space Administration (NASA), USA,
4. United States Geological Survey - Eros Data Centre, USA,
5. European Communities Joint Research Centre, Ispra, Italy.

All these agencies monitor vegetation and its rate of change through the seasons on a regular basis. Data is calibrated on the Normalised Difference Vegetation Index (NDVI) and the Global Vegetation Index (GVI) systems.

3.5.1.5 Global Vegetation Index

This dataset is collected by NOAA using the AVHRR data of fairly coarse resolution (greater than 15 km pixel size) which have been collected every week, on a global basis, since 1982. Initially, work was carried out on a continental scale and was used to show seasonal variations in vegetation.

On a sub-continental scale, the NASA/GSFC Global Inventory Monitoring and Modelling Systems (GIMMS) has been used to stratify cover types for eight countries in southern Africa, as a basis for estimating the supply of fuel wood. An improved (higher resolution) version of this database is planned for the near future. This will comprise Global Area Coverage (GAC) with a resolution of 7.6 km.

A joint project (NASA/NOAA) called Land Pathfinder is being created to act as precursor for the International Earth Observing System (EOS). The plan is to generate a global data set at 9 km resolution backdated to 1982. A similar product is being developed at ISPRA, the European Community's Joint Research Centre, where a scheme known as Monitoring Tropical Vegetation (MTV) has produced a daily GAC of West Africa between 1981 and 1989. This is being extended to cover the whole of Africa with a resolution of 5 km.

All current datasets are summarised in Appendix 10[5].

3.5.2 Databases on Agriculture

Nearly all nations possess agricultural databases of some description. These vary enormously, some crudely reflecting farming at a subsistence level and some giving precise details of cash crop production for export. Statistics on agricultural production are kept because governments typically regard agriculture both as being of national importance and as being a source of potentially taxable revenue. The quality of the data is, however, variable. It is dependant on the nature, and particularly on the price of the agricultural products and on the degree of sophistication of the archiving system.

Data collected on a national basis are archived in government departments within a particular state where they form the basis for larger regional and international databases. At an international level, the main databases on agricultural products and related information are run by the OECD, UNEP and FAO. The FAO is the primary source and the other organisations tend to use data from it.

Agricultural production statistics are complex and need simplifying if they are to be used for monitoring compliance with agreements designed to limit greenhouse gas emissions from the agriculture sector. As in the case of other emission sectors, the task of simplifying the data is made easier if the sector is first broken down into subsectors, each comprising a main source, which can then be considered individually in some detail. There are four main emission sources in the agriculture sector:

i) fertiliser use (which releases nitrous oxide),

ii) enteric fermentation in ruminants (which releases methane),

iii) rice paddies (which give off methane), and

iv) agricultural waste (which emits both methane and carbon dioxide).

Data on all four subsectors are compiled in considerable detail by the FAO and are generally broken down into national and regional 'bands'.

Some of the subsectors are difficult to monitor using remote sensing (for example, the 'fertiliser use' subsector) and will probably be assessed mainly by ground based methods, coupled with other indirect sources of information, such as trade statistics. Other subsectors, notably those associated with growing crops, are more amenable to monitoring by remote sensing, For example, remote

5 The ES/EDC programme in the USA is currently compiling a 1 km dataset of the entire surface of the Earth. An example of sort of the breakdown used in land cover classification is given in Appendix 9.

sensing is well suited to measuring both the areas (and changes in area) of rice paddies and to establishing when the rice is no longer being grown. It would therefore be appropriate to monitor methane emissions from rice paddies indirectly using remote sensing, coupled with ground truthing measurements. The FAO categorises rice paddies under the heading of 'Irrigated Land' and breaks down data on the subject into considerable detail, allowing a month by month picture to be obtained of rice production at any particular time. Data such as this could be used to supplement remotely sensed data.

Other information of relevance to greenhouse gas emissions which is collected by the FAO (in addition to data on cereal production appropriate to rice paddies) includes:

i) data on fertiliser sales, and

ii) data on livestock numbers.

3.5.3 Databases On Waste

There is, at present, little data on the Waste Sector in general and on animal waste in particular. Waste could be a sizeable source of both methane and carbon dioxide and further work on collecting data for the sector is needed. Proper monitoring of the sector would require extensive ground observation of waste containing sites (landfills, lagoons, biogas treaters etc.). Satellite based remote sensing might be used to monitor larger sites on a regular basis where it could be particularly useful in detecting changes in the use of the sites.

In the UK, the Department of the Environment is shortly to start the compilation of a register of 'potentially contaminated land'. This will include all waste handling sites in the UK. There are plans for a similar future project that might include all such sites in Europe.

The FAO attempts to catalogue animal waste generation and storage but these data are simply presented as a total for each nation and are not geo-referenced.

4. Verifying Baseline Data

This section addresses the problems associated with verifying baseline data. Without accurate and verifiable baseline data all subsequent measurements of changes will be subject to error. Factors which affect the accuracy of baseline data vary from sector to sector depending on the characteristics of the emissions sources and the data collection methods used to measure them. The problems associated with measuring each sector are therefore considered separately, after first addressing the potential problem of compatibility between datasets from different sectors.

4.1 Issues in Verifying Baseline Data

Two main issues need to be addressed when setting up a 'baseline' for a particular set of data (irrespective of the nature of the data). Firstly, it is necessary to set a realistic baseline year for the sector under consideration - assessing rice paddies in a year of abnormally severe drought would not, for example, be appropriate. Secondly, the verifiability of the sector must be assessed. This involves setting practical limits on the data that is needed for a particular task. It would be pointless, for example, to collect data of such high resolution that it could not all be used. Conversely, any monitoring procedure must be sufficiently accurate and comprehensive to enable effective measurement of emissions from a particular source. In essence, assessing verifiability entails ensuring that appropriate monitoring methods and procedures are applied to a particular sector. For example, the spatial resolution for a global dataset will generally be lower than that required for monitoring 'hot spots'.

Once a baseline date has been chosen, an initial dataset must be compiled. It is rarely possible to use a single technique or mutually compatible techniques for all data collection exercises and problems are thus likely to arise due to the incompatibility of the components of the dataset. Prior to its compilation the following questions therefore need to be answered:

i) will the same standards of detail and quality apply to all data sources?

ii) are the data collection techniques used for compiling the database mutually compatible?

iii) are the technologies used for data acquisition or compilation likely to change significantly in the future, rendering the original dataset redundant or of poor quality?

iv) is it possible to ensure that data gathered using one technique (such as remote sensing) can be cross referenced with data about the same site gathered at the same time and place but using another technique? (i.e. are the geo-spatial referencing systems equally accurate for all data?)

If a global dataset is to be compiled from national databases, it is first necessary to establish to what extent, if any, states over- or under-estimate their emissions. Countries may deliberately or accidentally build safety margins into their estimates, thereby giving a false baseline dataset. Errors due to 'creative accountancy' or the use of inappropriate methodologies can be extremely difficult to detect.

Apart from the potential problems of data compatibility and deliberate or accidental errors in national databases, inaccuracies are also likely to arise from the different ways in which data is acquired from different emission sectors. Some of the potential problem areas associated with the Forest, Agriculture and Waste Sectors are outlined below.

4.1.1 Forest Sector

A forestry database essentially consists of an inventory of the numbers, types and condition of trees. Compiling such a database is, however, a complex task. Some of the more important problems which are likely to arise in compiling such a database are outlined below.

Firstly, the database will probably be compiled from many national and regional databases which will vary in both size and detail. The datasets will have individual characteristics which reflect the tree populations of the regions involved and will probably have been compiled using different measurement methods. Also, techniques for counting and assessing the health of trees may differ from region to region, depending upon both the types of measurement methods used and the types of trees present. For example, it is considerably easier to count trees in a Scandinavian forest, which consists of only a few species of tree, than in the Amazonian rain forest where many species are present. Also, a Scandinavian forests is more accessible, enabling more efficient and accurate ground-truthing. Thorough and accurate referencing and classification of data is also likely to be essential.

To overcome potential classification problems, it would be sensible to adopt a single, widely used system such as that used by the FAO. An overview of this system is given in Appendix 3, together with a description of the categories. The advantage of this system over all others is that it is tried, tested and broadly accepted worldwide, and appears to cover all of the more numerous types of tree.

4.1.1.1 The FAO Classification System

The FAO classification system includes only vegetation which covers more than 10% of the ground area of a given site. It is taken that vegetation covering an area of less then 10% does not constitute a 'community' of plants. The system draws a distinction between 'natural' and man-made vegetation, the latter being referred to as plantations. It also distinguishes between trees and shrubs, where shrubs are defined as having 'little or no woody content'.

Trees are defined as: 'woody perennial plants typically large and with a single well defined stem carrying a more or less definite crown, height more than 7 m for mature trees.' Shrubs , on the other hand, are defined as being between 0.5 and 7 m in height.

It is possible to further break down the FAO category of trees/forest into subclasses containing species of trees. Individual species of tree can be detected by their distinctive 'crowns', by aerial photography (see Appendix 6).

A fuller description of the FAO classification system is given in Appendix 3.

4.1.1.2 External Events

Apart from classifying vegetation, it is necessary to take account of both natural and anthropogenic events that may occur in a forest and which could alter its structure (and hence its classification) within a fairly short timescale. For example, many forests undergo a natural sequence of events known as 'succession' in which their characteristics change over a period of time. This period varies for differing types of forest.

Natural phenomena such as storms and hurricanes can, of course, destroy large areas of forest in an extremely short period of time.

4.1.1.3 Deforestation

Like the 'external' events outlined above, deforestation is a phenomenon that occurs over a fairly short timescale. There are two main types of deforestation: clear-logging and selective logging.

Clear-logging involves felling all of the trees in a given area. It is comparatively easy to detect using remote sensors operating in the visible and near infra-red wavebands. The pattern of deforestation is usually distinctive, following a 'herringbone' pattern which is created by the construction of highways and smaller branch roads leading from them for the removal of trees. Similarly, forest clearance for agriculture or due to the encroachment of urban areas is distinctive and fairly easy to monitor using remote sensing. In addition, deforestation of this type can usually be detected from the smoke plumes which arise from burning of tree debris.

Selective logging is more difficult to detect than clear-logging because it involves the removal of single trees from amongst many others. However, because selective felling is usually performed to extract particular species of trees for the special qualities of their wood, all of the trees are normally removed from the forest. Access roads and/or river jetties are therefore needed for the removal of the wood and such features can usually be detected. Moreover, selective felling is not a significant source of greenhouse gas emissions - the trees removed are not typically burnt and other trees will naturally tend to regrow where older timber is removed. Indeed, selective felling may well result in more carbon dioxide being sequestered than if a forest were left undisturbed.

Increasing development of radar and lidar techniques in the future could lead to the introduction of sensors which could detect 'holes' caused by the removal of single or clumps of trees in the canopy of dense forest. Lidar has, for example, recently been used to estimate timber volumes by vertically profiling forests. The technique was capable of detecting gaps in the canopy with a height discrimination of 15 metres.

4.1.1.4 Pollution

Natural and anthropogenically introduced 'pollution' affect the condition of forests and should therefore be taken into account by any monitoring programme. Tree death or damage caused by anthropogenic pollution such as acid rain must obviously be accounted for but so must naturally occurring diseases which can have an equally devastating effect. Damage caused by pollution does not, of course, usually lead to greenhouse emissions but it must be noted by any monitoring regime in order to avoid counting it in with deforestation and other phenomena which do lead to emissions. For similar reasons commercial forestry or plantations must also be noted - even if the products from them are not burnt or left to decay.

4.1.1.5 Summary of the Forest Sector

The main difficulties in compiling a global database on forests is likely to be due to:

1) the incompatibility of data from different sources,

2) obtaining a sufficiently accurate set of geo-referenced data.

If these difficulties are not overcome to a large extent then data collected by satellite will be of limited value. Indeed, the same applies to data collected on the ground.

4.1.2 Agriculture Sector

The Agriculture Sector can be considered as another type of land use and can thus be treated in much the same way as the Forest Sector. The United States Geological Survey (USGS) has, for example, adopted a very flexible classification procedure that could be applied to both the Forest and Agriculture Sectors. It divides land use into five major categories which are further broken down into 37 sub-categories (see Table 3.5, Appendix 9). The USGS system will be operated as a 1 km dataset and will attempt to give global coverage.

Classification of the various forms of agricultural land depends largely on land use. There are two main types of farming practice: intensive (which is also usually large scale) and subsistence (small scale). The predominant type of practice determines the scene size which any remote sensing system must use. The predominant crop types will then determine the types of sensor needed. Any monitoring regime must also take into account seasonal variations in crops and other types of, or changes in, land use (recreational, set-aside, waste disposal etc.).

Some problems are likely to arise in verifying data from the Agriculture Sector which are distinctly different from those in the Forest Sector. The first of these is that the size of the objects which need to be detected is typically smaller and, therefore, both geo-referencing and detection are more difficult for a monitoring system based on remote sensing. The second problem is that observable changes occur over a much shorter period than in the Forest Sector (typically annually or even monthly). This means that more data may have to be collected and processed, depending on treaty commitments. The fact that much of this will be at a relatively high resolution will pose additional problems with data storage. A third potential problem is likely to be that of ground-truthing a very large number of sites worldwide.

Monitoring crops poses few basic technical problems, although monitoring animal numbers would be more difficult, as was discussed in Section 3. The main difficulty in setting up an effective monitoring regime is likely to be devising means of collating and processing the large amounts of data required. There may also be difficulties in acquiring and ground-truthing data from poorer countries.

It should be noted that in monitoring compliance with an agreement regulating greenhouse gas emissions or sinks, the main agricultural sub-sectors of interest are rice paddies and ruminants. Verifying baseline data from these sub-sectors involves solving all of the problems outlined above but, because of the limited scope of these activities, difficulties associated with data collation and processing will not be as acute as they would be if the entire Sector were to be monitored. Moreover, international and regional databases relating to ruminant numbers and rice paddy areas are, at least, maintained. In general, these are based on reported national statistics and provide no independent check on data reported by states. However, there is some scope for validating local data through existing FAO and regional development programmes.

4.1.3 Waste Sector

Greenhouse gas emissions from the Waste Sector are almost all due to methane evolved from landfill sites. There are no means of monitoring such emissions directly or indirectly by remote sensing although it is possible to measure emissions using ground based equipment.

It would be possible to monitor the presence or absence of sites using remote sensing but this is probably only possible in the more developed countries where accurate records are kept of their location. (It is often difficult to distinguish between landfill site and other features in the absence of data acquired on the ground).

4.2 General Problems

The approach to verifying baseline data given in Section 4.1 will only give a 'snapshot' of the conditions pertaining to the three sectors under consideration at the time that the baseline data is collected. Constant 'updating' of information is thus required. Particular areas of forest or other types of land use can change with time. Such changes can occur for natural or artificial (anthropogenic) reasons. For example, changes in the EC the Common Agricultural Policy can lead to significant changes in land use in Europe, as will shortly occur as a result of the current 'set- aside' policy. Similarly, the previous Brazilian government policy of promoting forest clearance to make way for ranching and other agricultural activities resulted in a rapid and substantial change in both the Forest and Agriculture sectors for South America. Change may thus occur fairly quickly and any monitoring regime has to be capable of adapting to change within a fairly short period of time. Indeed, there are likely to be legitimate disagreements about areas devoted to particular uses within any given 'baseline year' and it is therefore important that baseline data is specifically agreed at an early stage of any negotiations.

Certain difficulties are likely to arise with any classification systems adopted. For example, the FAO system of defining a forest as being a group of trees which covers more than 10% of a given area of ground is not such a clear cut system as it first appears. Neither remote sensing nor ground-truthing methods could, at present, be used to precisely define all of the worlds' forests on this basis and, more importantly, it would be difficult to apply error bounds to any resulting figures. Questions which immediately arise are: i) can satellite based sensors differentiate between 5% and 15% canopy cover? ii) how does one monitor coverage in the case of a multilayered canopy? iii) is it possible to distinguish easily between different species of trees and hence monitor changes in forest type (and thus biomass per unit area)?

All of these questions are likely to be difficult to answer. Many open formations of forest comprise a mixture of trees and shrubs and the dividing lines between differing types of vegetation are often blurred. Distinctions between different types of trees are often easier (for example, conifers can usually be distinguished from broadleafed forest) but the boundaries between the two may, again, be indistinct. This type of problem might appear to diminish if any agreement to limit greenhouse gas emissions includes provisions simply to define preserved areas of forest, in fact this is not so because the biomass of the forest could change. It is therefore essential to the success of any such agreement that the greenhouse gas emission potential of the forest is monitored and to ensure that the types of trees in a protected area do not change significantly.

Plantations are a sub-group of forests that deserve special attention because of their unique characteristics. Plantations are commercial enterprises which need to have a rapid 'turn-over' in order to be commercially viable. The frequency of tree felling in such areas must be taken into account by any monitoring system to avoid deforestation/reforestation cycles being interpreted wrongly. Categorisation of plantations may also prove difficult. The FAO categorisation stipulates a minimum area for plantations of 0.5 hectares - although reasonable for, say, eucalyptus plantations it begs the question of how to categorise other anthropogenic features such as hedgerows and rows of trees in the form of windbreaks.

To some extent increased ground truthing will help to shed light on the sort of potential problems outlined.

4.3 Database Representation

The Forest and Agriculture Sectors are parts of the larger 'Land Use' grouping and can be treated as such when compiling inventories. Their distinct characteristics require that data for them are collected in somewhat different ways but it is essential that the sets of data are in compatible formats.

The GRID approach to storing information on land use is probably the best available. This employs separate 'layers' of data each representing different types of land use and changes to it. Coupled with an extensive inventory system such as that used by the FAO, it could form the basis for an easily accessible but comprehensive database for most types of forest and agriculture.

5. Verifying changes in forest areas and agriculture

The information required for verification is collected in a three stage process: data acquisition, data collation and data assessment (including independent checking). This section examines problems that might arise at each stage of this process when it is applied to verifying changes in forest areas and agriculture. Potential political and economic problems likely to adversely affect verification are also assessed, in outline, as are some issues in reporting procedures and organisational structures, although these are dealt with more fully in the next main section.

It is assumed throughout this section that the main international method for collecting 'independent' data will be remote sensing, backed up by ground truthing.

5.1 Data Acquisition

The main issue in using remote sensing as a means of acquiring data is the degree of discrimination that can be achieved. This, in turn depends on the spatial and spectral resolution of the instrumentation available and on their operational wavelengths. As the resolution of the instruments required for monitoring forests is generally dissimilar to those for monitoring agriculture, the two sets of requirements are discussed separately, below.

5.1.1 Forests

5.1.1.1 Spatial Resolution

A spatial resolution of about 10 m is required for measuring changes in the areas of dense forest, as mentioned in Section 3.2. Many satellite borne sensor systems carry instrumentation with this degree of resolution and airborne systems can carry instruments with a far higher resolution. There are thus likely to be few fundamental difficulties associated with monitoring changes to dense forest, in terms of the resolution of available instrumentation (although some detailed problem areas are outlined below).

Destruction of dense forests occurs in three main ways: wholesale clearing, encroachment inwards from the perimeter, and selective felling from within a forest. It is fairly easy to detect wholesale clearing and any significant encroachment using satellite based sensor systems. Detecting selective felling of trees is more difficult using space based systems but comparatively simple using airborne ones. A two tier system employing both types of system, of the type mentioned in Section 3.2, is therefore likely to be effective in detecting changes in forest area. Success is not, however, certain. Selective felling of single trees would not normally be detected by satellite and attempting to survey the world's forest from the air would be extremely costly. If selective felling were to be widely adopted it would consequently be difficult to monitor. Such an eventuality is, however, unlikely because if many trees were cut roads would be needed for their removal, and such new roads would be detectable by satellite based systems.

Measuring changes to the areas of 'open forests'[6] poses problems for space based sensor systems. Small, fairly isolated stands of trees are difficult to detect by satellite based sensors because many such stands have a maximum dimension of less than 10 m. The removal of the stands would therefore be similarly difficult to detect. Also, even if the clumps of trees were relatively large and detectable, there would usually be many of them. Simply identifying large numbers of small stands is likely to be difficult, as is registering their position accurately as part of a georeferenced data storage system. Open forests could be detected quite easily using airborne sensors but referencing the data would still pose problems, as would storage of the large amounts of data that would be amassed. There is no simple and obvious solution to these problems.

All trees do, of course, die. From above, it is very difficult to discriminate between those which fall due to natural causes and those which are felled selectively. This is likely to be a significant problem to any monitoring regime employing high resolution remote sensors and ground based verification is the only sure way of ascertaining the real cause. In practice, it might be simplest for a monitoring regime to ignore the isolated fall of individual trees, whatever the cause.

5.1.1.2 Spectral resolution

When observing trees from above, the main features which distinguish them from other types of ground cover are the characteristic spectral signatures of their foliage in the visible and infra-red wavebands. Many satellite and air borne sensor systems are capable of distinguishing these signatures from those of other types of foliage and are therefore basically well suited to monitoring forest areas. However, the spectral characteristics of forest foliage can vary considerably due to natural phenomena and it is important that any monitoring system is capable of distinguishing between natural and anthropogenic changes.

Two main types of change occur naturally in the foliage of trees: those due to disease and those due to the annual fall of leaves from certain species. Both can result in the complete loss of foliage, which could be mistakenly identified as deforestation by a monitoring regime based on foliage identification. This sort of mistake is unlikely to occur in the case of seasonal defoliation in temperate,

[6] Open forests have trees covering about 10% of ground area. There are large areas of open forest all over the world and their burning would release very large amounts of carbon dioxide, quite apart from eliminating them as sinks.

deciduous forests where the time at which leaf fall occurs is predictable and occurs in all trees at more or less the same time. However, many species of tree in tropical forests shed their leaves annually but not in unison. Different trees can, and do, shed their leaves at different times of year. It would be difficult to distinguish this natural phenomenon from selective tree felling using satellite based remote sensing systems operating in the visible and near infra-red wavebands. It might therefore be necessary to check such phenomena by airborne remote sensing, which would be costly. Alternatively, it might be possible to check on the comparative change in surface roughness of the areas using satellite borne radar. The effectiveness of radar in this sort of application is not, however, established.

The same types of solution as those proposed above might also be employed to distinguish between diseases in foliage and the anthropogenic removal of trees. In general, however, detecting disease poses fewer problems than detecting isolated cases of annual defoliation because leaf loss and discoloration is rarely total and, when it is, it tends to occur in many trees covering a large area and can be detected by satellite systems.

In practice, the only effective solution to the problem of localised defoliation due to disease or annual leaf fall would probably be to ignore it. Defoliation or deforestation over areas of less than, say, 20 m maximum dimension might be discounted, whatever its cause. This approach would, however, bring its own problems, the most important being that selective tree felling could not be assessed. In temperate and boreal forests where leaf fall only occurs annually, or is due to disease, the problem is less severe and a solution of the type outlined may not be needed. In tropical forests, however, the problem must be addressed.

5.1.1.3 Atmospheric interference

Cloud cover, haze and other atmospheric phenomena can limit, or even prevent, observation of the ground by remotely based sensors operating at visible and infra-red wavelengths. These types of phenomena pose particularly severe problems when attempting to observe rain forests, where there is significant cloud cover during the course of most days. Cloud can also obscure temperate and boreal forests. Any monitoring regime employing satellites will therefore have to attempt to obtain images of any particular site far more frequently than it might need to under ideal atmospheric conditions, and even then high quality images might not be obtained.

In winter, temperate and boreal forests are likely to be under snow which severely inhibits spectral analysis of foliage. This problem and that posed by cloud cover can be overcome by using radar which will give a clear indication of forest cover in almost all weather conditions. Radar does not, however, allow the foliage of trees to be observed and should consequently not be used as the sole technique for monitoring forests.

5.1.1.4 Summary of main issues in monitoring forests

i) Detecting selective felling of trees in tropical forest is likely to prove difficult using satellite based instruments. This is not primarily because of the lack of resolution of such instruments but because of the annual leaf fall from trees occurring in such a way that it could be confused with deliberate deforestation. Airborne instrumentation could discriminate between the two different types of phenomena but it would be extremely costly to use aircraft for this task.

ii) It will be difficult to measure 'open forests' by satellite based remote sensing and very expensive to do so using airborne instruments.

iii) Cloud cover and other atmospheric phenomena are likely to impede, but not necessarily prevent, forest monitoring using remote sensing. For these and other reasons it is likely to prove necessary to monitor temperate and boreal forests mainly during the summer. All sites will need monitoring more frequently than would be the case in uniformly fine weather in order to increase the chances of obtaining clear images.

5.1.2 Agriculture

5.1.2.1 Spatial Resolution

The spatial resolution required to detect crops and domestic animals is, in theory, about one metre. In practice, this degree of resolution would give rise to far more data than could realistically be processed by any monitoring regime using space based remote sensors, as mentioned in section 3.2. It is therefore more likely that a resolution of 10 m will be used. This would be adequate for measuring relevant types of crops (with the provisos given below) but is inadequate for counting ruminant numbers and the task would best be performed using a combination of airborne remote sensing and ground based assessments.

Counting animal numbers by airborne remote sensing is likely to be costly and is therefore unlikely to be performed frequently. It is therefore important that it is done with reasonable accuracy. When attempted, ground truthed counts of herds of large wild animals have proved quite accurate, for example those performed in the Serengeti Plains were deemed accurate to within $\pm$ 10%. However, these censuses were carried out in almost ideal weather conditions and with little ground cover to obscure the animals. In wooded areas such counts are likely to be significantly less accurate. Infra-red sensors could give enhanced accuracy by locating animals due to their radiated body heat (even when the animals were under light cover) but it is difficult to ascribe a specific degree of error to this sort of measurement.

It is not possible to reach a general conclusion about the accuracy of airborne remote sensing of animal numbers - if for no other reason than it will often to be difficult to discriminate between different types of animal prior to counting them. In some cases an acceptable degree of accuracy could be probably achieved fairly easily and in others any sort of count would be impossible. It would therefore be better to use ground based counting techniques as the main type of evaluation method and to supplement this with airborne remote sensing where applicable.

By far the most important type of land use, in terms of greenhouse gas emissions, is rice growing, which gives rise to methane. Other types of land use are not therefore considered here. Indeed, only rice grown in paddies fields (i.e. wet rice fields) is considered because rice varieties grown under dry conditions emit almost no methane. Strictly speaking, biomass burning should be considered by any monitoring regime, but most burning carried out as a result of agricultural activities is performed on a very small scale in a great many different locations and it would be almost impossible to keep track of such activities.

Most individual rice paddies are fairly small (of the order of ten metres maximum dimension) especially in developing countries. However, the fields are usually grouped together in large numbers (one hundred or more) in order to make them easier to irrigate. Most rice paddies (probably more than 90%) could therefore probably be detected by satellite based remote sensors.

5.1.2.2 Spectral Resolution

Infra-red remote sensors operating in the wavelength range 3 to 30 μm would enable the body heat from animals to be detected and would therefore probably be the most appropriate type of sensor to use for counting animal numbers. Ruminants under light cover such as woodland trees could then be detected. Wherever possible it would be better to use detectors operating at the shorter wavelength end of the range, even if this meant losing some spectral resolution, because the spatial resolution of infra-red sensors increases with decreasing wavelength.

Animal numbers fluctuate, usually on a seasonal basis. It is therefore important that any monitoring regime always makes measurements at the same time of year.

Microwave sensors in the form of radars are particularly appropriate for monitoring rice paddies because these are usually partially covered by water. Microwaves reflect well from water and a strong signal is thus assured.

Moreover, many paddies are sited in areas where there is frequent cloud cover, which microwave radar can penetrate and most other types of sensor cannot.

It would be advisable to use visible/infra-red systems, in addition to radar, in order to detect the rice plants, rather than the water in the paddies. This would cover the eventuality where paddies were flooded but no rice was being grown. Rice is typically cropped more than once each year but is replanted and there is thus no reason to assess the presence or absence of crops routinely. It is, however, important to establish whether crops are permanently absent, although if paddies are unplanted it would be unusual for them still to be irrigated.

5.1.2.3 Summary of Main Issues in Monitoring Agriculture

i) It is likely to prove impractical to detect animals, and hence count ruminant numbers, by space based remote sensing. Airborne remote sensing using infra-red sensors would generally be preferred for this application but would not be suitable for cases where the animals were 'stabled' or in dense woodland. Counting methods should thus be primarily ground based although it would be cheaper and easier to use airborne sensors for spot checks where appropriate.

ii) The area of rice paddies could be assessed by space based remote sensing. Radar is best suited to the purpose but should be 'backed up' by measurements in the visible/infra-red wavebands.

iii) All sectors need corroboration by data collected by ground based methods.

5.2 Data Collation

The main questions which arise in data collation are: i) how to collect the data and in what form, ii) where and how to store the data, and iii) how to ensure that it is of sufficient quality for subsequent processing and analysis.

The data acquired by air and space borne sensor systems is likely to be in a variety of different formats and will initially be collected at many different sites (airfields, ground receiving stations etc.). Before it can be analysed, the information will first have to be assembled in one place, or perhaps a few places worldwide, and then processed into a single format or a set of compatible formats.

Most data acquired by satellite will be in an electronic digital format which can be turned into an image. Data in this form can be processed easily without losing information and is easy to transmit by radio or landline, again with little or no loss of information. It would therefore be sensible for all data, including that from airborne sensors, to be converted into this sort of format as soon as it is received, as outlined in Section 3.

Digitised electronic data is fairly easy to store without loss of information. Also, it takes up very little storage space and is easy to process rapidly. The quality of such data depends mainly on the sensors from which it is received.

There appear to be no fundamental technical problems associated with collating data from a monitoring regime based on remote sensing. The cost of installing a suitable system could, however, be high.

5.3 Data Assessment

In this Section some basic questions of how to assess data on vegetated areas and animal numbers are addressed, in outline. Further discussions of questions of exactly how to measure increases or decreases in area are given in following sections.

Assuming that data is stored in a digital electronic form which can be presented as images on cathode ray tubes, as mentioned in Section 5.1.2, it would probably be simplest to measure changes by comparing layers of images taken at different times. For example, a recent satellite image of a forest would be superimposed on another older image and any changes noted. This type of process can, to a large extent, be automated. 'Masks' of areas of interest can be recorded, superimposed on new images of the same areas, and any changes measured automatically. Such assessments should not, however, be entirely automated because a machine cannot pick out unusual changes or abnormalities for which it has not been programmed, whereas well trained operators could.

A data assessment system of the type outlined could be accurately georeferenced and could enable rapid, almost entirely unambiguous, comparison of temporally different sets of data. It would, however, be difficult to use the data layering method for counting animal numbers. In this case, straightforward counts from images, or on the ground, would be more appropriate. Automation of this task would probably not be possible.

In assessing animal numbers it will be important to define the areas in which particular herds are kept. The size of these areas can very enormously and some will be very large. Many nomadic people, such as the Maasai in Eastern Africa and the Lapps in Scandinavia, move their beasts over many hundreds of kilometres, often over international borders. Similarly, many cattle ranches in both Africa and the Americas are vast. Establishing where animals might be within such areas and avoiding double counting are likely to pose problems for any monitoring regime.

In assessing changes in area it is important to define exactly what constitutes a change. This will be dictated mainly by the accuracy of the data. For example, with most satellite based systems any spatial change of less than ten metres would be ignored, even if such a change appeared on a monitor, because the resolution of the sensors would only be ten metres. Changes of less than, say, 20 m in dense tropical forests might also be ignored lest annual leaf fall from a particular type of tree be confused with tree felling, as mentioned in Section 5.1.1.

When assessing data relating to changes it is necessary to decide not only how to measure changes but also how often to measure them. If there is too long an interval between assessments, small changes that could easily be rectified at an early stage may grow to unacceptable proportions. If the interval is too short the process is likely to be costly. Setting an appropriate interval is likely to be crucial to verification related monitoring of forests and land use.

In addition to defining an appropriate measurement interval in the forest and agriculture sectors it is also important to set appropriate dates, or at least seasons for monitoring. Most living systems change seasonally. The appearance of foliage can change considerably, or even disappear, and animal numbers typically increase in springtime. Generally, errors caused by such phenomena can be minimised by always making measurements at the same time of year, preferably when a particular feature of the objects being monitored is most easily distinguished by remote sensors. It would not, for example be sensible to monitor temperate forests in winter although, because of the absence of cover, it might well be advisable to count animal numbers during winter.

5.4 Some Political and Economic Factors

Any independent regime designed to monitor forest areas and land use will possess several features which have important political and economic implications. This is particularly true of a regime based on the use of remote sensing techniques. Some of the more important issues that must be addressed if such a regime is to be set up are listed below.

i) **Overflights.** Most nations do not like to have data gathering activities conducted on their territories by nations other than themselves. Any independent monitoring regime involving remote sensing must therefore incorporate agreement that the permission of individual nations would be granted, under acceptable constraints, for any overflights and for the use of any data obtained. The co-operation of the states involved is, in any case important. Data gathered without ground truthing may be unreliable and ground truthing cannot be carried out without the permission and active participation of national governments.

ii) **National policies on forests and agriculture.** It is important that national polices on forests and land use take into account the requirements of any monitoring regime and vice versa. For example, a particular country might decide to move some rice production to an area served by a new dam and irrigation scheme. The task of a monitoring regime would be much easier if such a change was notified in advance and in some detail.

iii) **Data acquisition on the ground.** As mentioned previously, ground based data collection is essential for both ground truthing and baseline data collection. It will therefore be necessary for a monitoring regime to liaise closely with relevant national authorities on how to effect data collection in the most efficient way.

iv) **Cost sharing.** A fair and equitable scheme must be devised for sharing the costs of a independent monitoring regime and for mounting nationally based monitoring efforts.

6. Discussion and Conclusions

6.1 Discussion

This discussion presupposes that treaty commitments relating to emissions from forests and rice paddies are expressed in terms of areas and types of vegetation and that commitments relating to emissions from ruminants are expressed in terms of numbers and types of animals, as discussed in Section 2. As landfill sites and fertiliser use are best monitored by direct and indirect measurement methods, respectively, they are not discussed here although they are mentioned in the conclusions to this report.

6.1.1 Forests

6.1.1.1 Baseline data and databases

In setting up a 'baseline' for any set of data it will first necessary to choose a typical baseline year. (In the case of forests this basically means that years in which weather conditions are abnormal or plant diseases are unusually widespread should not be used for data collection.) It will then necessary to collect data and assemble it into a database which, in the case of forests, will consist of an inventory of the numbers types and condition of trees.

The database will probably be compiled from many national and regional databases which will vary in both size and detail. Lack of compatibility between different sets of data will therefore be a problem. The datasets will have individual characteristics which reflect the tree populations of the regions involved and will probably have been compiled using different measurement methods. Also, techniques for counting and assessing the health of trees may differ from region to region. To overcome potential classification problems, it would be sensible to adopt a single, widely used system such as that used by the FAO.

In addition to classifying vegetation, it will necessary to distinguish between natural and anthropogenic events that may occur in a forest and which could alter its structure (and hence its classification) during the period that baseline data is being collected. The effects of pollution could, for example, be confused with the effects of naturally occurring disease.

The main problem in assembling and compiling baseline data is likely to be obtaining sufficient resources to make the information sufficiently accurate and comprehensive for effective verification.

6.1.1.2 Measuring Changes

There are few fundamental problems associated with monitoring changes in forest areas caused by wholesale clearance or encroachment from the perimeter of wooded areas, assuming fairly large total areas of relatively dense forest. As discussed in Section 5.1, changes in area of these types could be monitored primarily by space based remote sensing systems with a spatial resolution of about ten metres, backed up by occasional airborne remote sensing. The extent of changes in area could be assessed by superposition of the most recent image of a scene upon a baseline image, probably using an automated or semi-automated forest 'masking' routine. The main potential sources of error would be the spatial resolution of the sensors, the prevailing atmospheric conditions (the presence or absence of cloud or haze) and the condition of the remaining standing trees, in particular whether or not deciduous varieties were in leaf. Except in cases of prolonged adverse weather conditions, errors due to all of these sources are likely to be small and could be quantified accurately.

Using space based remote sensing, it would be difficult to detect selective tree felling within any type of forest and, when detection was possible, to discriminate between felled trees and those which died from natural or other anthropogenic causes. It would also be difficult to monitor changes in the area of open forests, unless they were large. These phenomena could be monitored by airborne remote sensing but this would be costly and, if performed regularly, it would generate large amounts of data.

On balance, given the size of the errors which could arise, it would probably be prudent not to try to monitor selective felling at all nor to attempt to monitor open forests with any degree of accuracy. Most selective felling carried out on a significant scale is, in any case, for the purpose of obtaining hardwoods which are not typically burnt. Such activities are thus irrelevant to any regime designed to limit greenhouse gas emissions. Trees felled during the clearance of open forest are typically burnt and give rise to greenhouse gases. However, the total volume of wood that can be obtained from a given area of open forest is considerably less than from the same area of a dense forest and the amount of carbon dioxide evolved is therefore also considerably less. Moreover, open forest is not normally cleared on a large scale because its presence does not usually conflict with agricultural activities, the expansion of which is the main cause of the most deforestation.

6.1.2 Agriculture

6.1.2.1 Baseline data and databases

The Agriculture Sector can be considered in much the same way as the Forest Sector. Some of the problems that may arise in verifying baseline data are, however, different. The first of these is that the size of the objects which need to be detected is typically smaller and both geo-referencing and detection are thus likely to be more difficult. Also, the quantity of data is likely to be greater. The second problem is that observable changes occur over a much shorter period than in the Forest Sector This means that more data may have to be collected and processed in a shorter baseline period. The third main problem is likely to be that of acquiring accurate and comprehensive data from developing countries.

As the main agricultural sub-sectors of interest are rice paddies and ruminants, verifying baseline data will not be as acute as they would be if the entire Sector were to be monitored. Moreover, international and regional databases relating to ruminant numbers and rice paddy areas are, at least, maintained. In general, these are based on reported national statistics and provide no independent check on data reported by states. However, there is some scope for validating local data through existing FAO and regional development programmes.

6.1.2.2 Monitoring changes

Monitoring changes in the areas of rice paddies by remote sensing should prove fairly straightforward but assessing changes in fertiliser use, ruminant numbers, or the area of landfill sites is likely to be difficult. Landfill sites and fertiliser use would, in any case, be best monitored by other means (as mentioned in Section 2) and only the means of assessing rice paddies and ruminants are therefore considered here.

Ruminants

Counting animal numbers is likely to be impractical using space based remote sensing: satellites presently available and those likely to be available in the foreseeable future lack the spatial resolution for detecting animals. Moreover, even if high resolution sensors were available the amount of data that would need to be generated in order to count animal herds effectively would be considerable and consequently difficult to handle. Airborne remote sensors do have sufficient resolution to enable animal numbers to be counted but, again, would necessarily have to generate large amounts of data if the assessment task were to be performed adequately on a global scale. Airborne remote sensing should probably be used only where verification using ground based methods is impractical or difficult and where naturally prevailing conditions make remote sensing an attractive proposition.

In practice, airborne remote sensing of ruminants is likely to be most effective in cases where animals are kept in open, relatively treeless, countryside and where the weather is clear for significant periods of each year. These conditions correspond to those of larger scale cattle ranching and sheep keeping activities, where verification related monitoring would normally be difficult (farmers count their stock during infrequent 'round-ups', but these counts are difficult to check without large numbers of peripatetic staff with a sound knowledge of local farming practices). It would thus seem appropriate to use airborne remote sensing for monitoring this type of activity.

Assuming clear weather conditions, the principal errors associated with gathering data on animal numbers are likely to be due either to missing herds altogether or to double counting them. As was mentioned in the previous section, many cattle ranches are vast, sometimes extending over thousands of square kilometres. Location of herds may therefore be time consuming and difficult. Also, many of the grazing lands used by nomadic peoples overlap one another and the herds in them merge together and then fragment frequently, making double counting likely unless counting is performed within a short period of time.

If counting and data gathering procedures are accurate there will be no particular difficulty in establishing whether animal numbers have increased or decreased.

Rice Paddies

As was mentioned in Section 5, it would be possible to monitor most wet rice paddies (probably 90%) with space based remote sensing, particularly with radar which will both penetrate cloud cover and give a strong signal from the waterlogged fields.

There are likely to be few problems associated with measuring changes in the areas of paddies other than that of discrimination in the case of small area fields. In practice, however, this is unlikely to be a significant source of error because of the way in which paddies are usually cultivated: in large groups of fairly small area fields with their water coming from a common irrigation scheme. In such cultivation systems it is rare for paddies to be abandoned or fall into misuse singly or in small groups because as long as the irrigation system (which is the most expensive component) is functioning it is efficient to maintain as many fields as possible in operation. The primary, almost sole reason, for paddies falling into disuse is deliberate or accidental cessation of the water supply. When this occurs, large areas simultaneously stop being cultivated and it is thus fairly easy to detect any decrease. Moreover, because water no longer remains in the fields, it would be simple for radar remote sensing to detect any change.

6.2 Conclusions

Any agreement to limit anthropogenic greenhouse gas emissions from forests, rice paddies or ruminants should specify national commitments in terms of vegetated areas (and types) or animal numbers (and types) rather than emissions. This approach would obviate the need for the repeated use of inaccurate emission factors. Emissions from landfill sites could be measured more accurately and relatively efficiently by direct measurement methods and treaty commitments should therefore be in terms of emitted mass of gas. Emissions from fertiliser application should also be specified in terms of mass of emitted gas although in this case the most efficient measurement method would be indirect measurement based on fertiliser production or use.

It would be fairly straightforward to detect changes in areas of dense forest and rice paddies by space based remote sensing using operational or planned satellite systems. It would also be possible to monitor changes in certain types of large ruminant herds by airborne remote sensing methods. Atmospheric interference in the form of cloud is likely to be the most significant inhibiting factor in making such measurements in the visible or infra-red spectra. In many cases, measurements based on the use of microwave radiation are thus likely to be the more effective.

Changes in the areas of open forests and selective tree felling would be very difficult to measure using remote sensing and would probably not be worth monitoring. In the most widespread types of selective felling the trees are not burnt and need not, therefore, be monitored under a regime designed to indirectly measure greenhouse gas emissions.

Currently available data collation and assessment facilities are not sufficiently comprehensive in scope for the task of verification. Fundamentally suitable collation and assessment techniques do, however, exist and suitable facilities could be established without significant research or development effort.

At present, all of the measurements made in the forest, agriculture and waste sectors would be subject to significant error. The main source of error are inadequate data collection methods and inadequate effort for data collection, collation and assessment. The accuracy of data could be considerably improved by increasing the resources available for gathering, assembling and analysing it.

APPENDICES

Appendix 1: Satellite Based Remote Sensing Systems

Satellites and their sensor systems are designed for a wide variety of different purposes. Those of interest in remote sensing of vegetation belong to a broad grouping of so-called Earth Observation Satellites which are designed to view features on or near to the surface of the Earth. Amongst other types of instrument, these satellites usually carry sensors which operate in the visible and infra-red bands of the electromagnetic spectrum. They also, increasingly, carry microwave radars. All three types of sensor can be used for monitoring both forests and land use. The basic characteristics of these sensors, their satellite 'platforms' and data handling systems are described below.

1. Sensors

The types of sensors which are most used in observing vegetation operate in the visible, near infra-red, and microwave wavelength bands of the electromagnetic spectrum, although other wavelengths are also used. (The 'thermal' infra-red band can be used to detect temperature differences, for example.) Visible radiation encompasses wavelengths in the range 0.4 to 0.7 micrometres (or microns, µm), near infra-red the range 0.7 to about 1.5 microns (other infra-red bands extend up to the far infra-red at about 500 microns) and microwave radiation is in the wavelength range 1 millimetre to 1 meter.

Sensors operating in the visible region of the spectrum enable a similar picture to that which might be obtained by eye and are particularly good for selecting types of vegetation by their spectral absorption and reflection characteristics. (Vegetation typically reflects strongly in the green, centred on 0.48 microns, and less strongly at the longer, red, and shorter, blue, wavelengths.) Different types of foliage also exhibit different characteristic absorption and reflection properties in the near infra-red waveband, hence the widespread use of sensors which operate in this region. Most microwave based sensors of relevance to the study of forest areas and land use are radars. In this application they are used primarily for determining differences in 'surface roughness' and hence differences in the morphology of vegetation.

All sensors are prone to error. Many errors are due to limitations in the design of sensors or their platforms and are, or can be, reasonably well defined in the engineering specification for a particular system. Others are dependant on the object or objects being viewed, their positions in space and time and the position of the spacecraft. Errors due to these causes vary and are consequently more difficult to identify precisely. Some of the more important sources of this type of error are outlined below.

Atmospheric effects can have an adverse effect on the performance of remote sensing systems. Electromagnetic radiation can be scattered, reflected or absorbed by the Atmosphere. Indeed, strong absorption by atmospheric gases in the 1.0 to 3.5 and 5.0 to 8.0 µm (micron) bands tends to preclude their use in Earth observation, as does ionospheric reflection of many longer (radio) wavelengths. In other wavelength ranges atmospheric effects are typically less critical but cloud or haze can, for example, obscure visible or infra-red observations in an unpredictable manner.

Other factors which can critically affect observation are the angle and intensity of radiation, both at the sensor and, in the case of reflected energy, the object being viewed. Judicious choice of viewing angle can, for example, considerably enhance the amount of detail visible in a radar image by increasing shadowing effects. However, a choice of viewing angle or atmospheric conditions is not always available. If possible, it is therefore advisable to have combinations of different types of sensor available, or even different satellites in dissimilar orbits, so that different systems can be used to circumvent these problems.

2. Platforms

In remote sensing the term 'platform' refers to the vehicle carrying the sensors which, in this case, is a satellite. Apart from engineering considerations, such as size and power supply capacity, the characteristic of satellites which has the most bearing on the performance of their remote sensing systems is their orbit. There are two main types of orbit: geostationary and polar.

A geostationary orbit is one in which a satellite maintains a fixed position in space with respect to the Earth. Consequently sensors on the platform always have the same overall view of the surface. To achieve a geostationary orbit a satellite must travel at the same angular velocity as that at which the Earth rotates and this entails raising the vehicle to an altitude of 35,900 kilometres.

From a remote sensing point of view, the main advantage of putting a satellite into a geostationary orbit is that it has a constant view of the same area of the Earth. It can be used for tasks where information is required about a particular location at frequent intervals, for example, in weather forecasting. The main disadvantage of such an orbit is that its altitude is necessarily considerable (36,000 km) and the spatial resolution of any sensors is therefore less than would be the case in a lower orbit.

A polar orbit is one which takes a satellite over, or near to, the north and south poles. Each orbit subtends a small angle with respect to the previous one, which results in the satellite travelling over a different part of the Earth (except at the poles) on each orbit. The most common orbit of this type is sun-synchronous, where the vehicle maintains a constant position in relation to the sun and the onboard sensors view successive 'swaths' of the Earth's surface, eventually covering its entire area. Polar orbits need only be at a sufficient altitude to avoid atmospheric drag and can thus be as low as about 150 km, although they are typically in the range 700 to 950 km.

Polar orbiting satellites have the advantage over geostationary satellites in that they are relatively close to the Earth's surface and the spatial resolution of images acquired from them can be, and usually is, higher. Also, they pass over the entire surface of the Earth. The main disadvantage of polar orbits is that they pass over any particular area relatively infrequently and may consequently not detect short lived phenomena.

Most satellites carry small propulsion units which enable their position to be varied. These are designed mainly to allow fairly minor changes in the attitude of the vehicles although they are used to alter the position of geostationary satellites relative to the Earth (for example, to a different latitude). In general, large scale manoeuvring is not, nor can be, undertaken.

3. Data acquisition and transmission

The detection components of most types of modern visible or infra-red sensor are made up of arrays of solid state electronic devices which are electronically scanned. Pictures or 'digital images' acquired in this way, as data streams, are fairly easy to transmit to receiving stations on the ground, where they can be stored, manipulated and enhanced by computers. (Similar data streams are acquired from radars and can be similarly processed.) Acquiring, processing and transmitting data in this way obviates the need for any substantial data storage facilities on spacecraft and few now have more than a limited data storage capability.

The spatial resolution of images derived from arrays of solid state devices is dependant primarily on the size of the individual devices and that of the image formed upon them by the radiation capturing and magnifying systems in the spacecraft. Each device measures the intensity of incoming radiation, in some cases over a broad spectral band and in others over a narrow band or even at a single wavelength (by using filters or device materials which are sensitive to specific wavelengths). Most spacecraft of potential use in sensing vegetation carry sets of sensors which are capable of discriminating between several different wavelengths and can thus pick out the characteristic reflection and adsorption of different types of foliage.

The spectral resolution of sensors is usually defined by the amount of detail in the intensity data which is transmitted to Earth from any particular solid state element in a sensor to form an image. The larger the amount of data on intensity going to any particular pixel (picture element) on a cathode ray tube, the greater the spectral resolution. The spectral resolution of most earth observation satellites is usually between seven and ten bits (128 to 1024 pieces of digital information) for each spectral band.

As most data from satellite based sensors is sent directly to the Earth, a network of receiving stations is needed to acquire the information. In the case of the polar orbiting satellites such networks have to be fairly extensive and global in their coverage. Once received, data is usually transmitted to a central point for storage, processing and distribution, although independent receiving and processing stations are quite common for certain types of satellite programmes (notably, meteorological satellites).

A considerable amount of processing is usually required in order to obtain the maximum amount of data from an electronic signal or signals containing an image. Not only may several sensors or wavelength bands be employed and need to be correlated in order to build up an overall picture, but a good deal of imagery is distorted when it is received and it requires correction. At a fairly simple level, for example, geometrical distortion can be induced by very slight changes in the attitude of a satellite and must be corrected after reference to the attitude sensors. This type of work is commonly performed by the satellite owners or their agents from whom complete images can be obtained. Images are usually classified and referenced according to one of a number of standard schemes. Precise, standard geographic referencing is, of course, essential to any work requiring accurate data on changes in forest areas or land use.

Appendix 2: Some Basic Physical Characteristics of Operational and Planned Earth Observation Systems

Satellite programme	Orbit type/height	Sensor types	Spatial resolution	Scene size	Temporal repetitivity
<u>EOS (USA)</u> Earth Observation Satellite	Polar Sun synchronous	Visible/infra-red/microwave radar and others			
Planned: EOS-AM: 1998- EOS-Color: 1998- EOS-Aero: 2000- EOS-PM: 2000- EOS-Alt. : 2002- EOS-Chem. : 2002-	Height unknown	EOS-AM, and probably others, will carry Moderate Resolution Imaging Spectrometer (MODIS) <u>and</u> other visible/i.r. instruments derived from NOAA AVHRR <u>and</u> Synthetic Aperture Radar (SAR) EOS-AM: will observe surface, clouds, aerosols, radiation balance EOS-Color: biomass/ocean productivity EOS-Aero: aerosols EOS-PM: precipitation, ice, sea EOS-Alt.: sea circulation, ice EOS-Chem.: atmos. chemicals	0.5-1 km (MODIS) 10-20m? (SAR)	Unknown- probably about 3000 km MODIS	Unknown EOS-AM over Equator at 10.30 hours EOS-PM over Equator at 13.30 hours

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Satellite programme	Orbit type/height	Sensor types	Spatial resolution	Scene size	Temporal repetitivity
ERS (Europe) European Remote Sensing Satellite	Polar Sun synchronous	Microwave radar & visible-i.r. radiometer and others			
Operational: ERS 1: 1991-date Planned ERS 2: 1994-	777 km	Synthetic aperture radar (SAR): c-band (5.3 GHz) Infra-red radiometer (ATSR): 10 bands 0.4-11.5 *microns*	26m (SAR)	99 km swath (SAR)	1 to 26 days Over Equator at 10.15 hours
FENG YUN-B (China)	Polar Sun synchronous	Visible/infra-red			
Operational: FY-B: 1990-date		2 off 5-channel NOAA type Advanced Very High Resolution Radiometers (AVHRR): 0.58-0.68; 0.72-1.1; 3.55-3.93; 10.5-11.5; 11.5-12.5 microns	1.1km local area coverage (LAC) 5 km global area coverage (GAC) if as NOAA	2000 km (approx.)	1.75 hours

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Satellite programme	Orbit type/height	Sensor types	Spatial resolution	Scene size	Temporal repetitivity
GMS (Japan) Geostationary Meteorological Satellite	Geo-stationary	Visible/infra-red			
Previous: GMS-1: 1977 GMS-2: 1981 GMS-3: 1984	36,000 km (approx.)	Visible and Infra-red Spin Scan Radiometer (VISSR): 8 visible (0.55-0.70) and 6 thermal (3.90-14.7 microns) bands	1 km visible 8 km i.r.	Limb to limb	30 min (approx.)
Operational: GMS-4: 1989-date	140°E	As above	As above	As above	As above
Planned: GMS-5: 1993- GMS-6: ?		As above	As above	As above	As above

CONTINUED ON NEXT PAGE

Satellite programme	Orbit type/height	Sensor types	Spatial resolution	Scene size	Temporal repetitivity
GOES (USA) Geostationary Operational Environment Satellite.	Geo-stationary (in pairs)	Visible/infra-red			
Previous: GOES 1-6: 1974-1986	35,900 km (over Equator)	Visible and Infra-red Spin Scan Radiometer (VISSR): 8 visible bands (0.55-0.70 microns) and 6 thermal bands (3.9-14.7 microns). Plus VAS atmospheric sounder	1 km (visible) 7-14 km (i.r.)	Limb to limb	30 minutes
Operational: GOES 7: 1987-date (to '93)	140°E (with Meteosat 3)	As above			
Planned: GOES-I,J,K: 1992/93/94- GOES-L,M: 1995/6?					
GOMS (Russia) Geostationary Meteorological Satellite	Geo-stationary	Visible/infra-red			
Planned: GOMS-1: 1992/3	36,000 km 76°,166°, 346°E	GOMS-1: visible 0.4-0.7 and infra-red 10.5-12.5 microns. GOMS-2 & 3: additional 6-7 micron band	1.25 km(visible)6. 35 km(i.r.)	13,500x13,500 km (limb-limb)	1 hour (approx.)
GOMS 2 & 3: unknown					

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Satellite programme	Orbit type/height	Sensor types	Spatial resolution	Scene size	Temporal repetitivity
IRS (India) Indian Remote Sensing Satellite	Polar	Visible/near infra-red			
Operational: IRS-1A: 1986-? IRS-1B: 1991-date	904 km 72°E	Multispectral scanner (MSS): 0.45-0.52; 0.52-0.59; 0.62-0.68; 0.77-0.86 microns	72.5x36.5 m	148x160 km	22 days Over Equator at 10.30 hours
Planned: IRS-1 C & D: 1994 & 1996		As above	IRS-1C: 10m		
JERS-1 (Japan) Japanese Earth Resources Satellite	Polar Sun synchronous	Optical/infra-red/microwave radar			
Operational: JERS-1: 1992-date	70 km	'Optical' Sensors (OPS): 4 visible & near i.r.: 0.52-0.60; 0.63-0.69; 0.76-0.86; 0.76-0.86 microns 4 shortwave i.r: 1.60-1.71; 2.01-2.12; 2.13-2.25; 2.27-2.40 microns and 1 stereo band	18x24 m (visible/i.r.)	75 km swath	44 days Over Equator at 10.30-11.00 hours
		Synthetic Aperture Radar (SAR): 1.275 GHz (L-band) off nadir angle 35°, H-H polarisation	18x18 m (SAR)	75 km swath	

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Satellite programme	Orbit type/height	Sensor types	Spatial resolution	Scene size	Temporal repetitivity
<u>LANDSAT (US)</u>	Polar Sun synchronous	Visible/infra-red			
Previous: Landsat 1: 1972-75 Landsat 2: 1975-78 Landsat 3: 1978-82	920 km	Multispectral scanner (MSS): 0.5-0.6; 0.6-0.7;0.7-0.8; 0.8-1.1 microns <u>and</u> 10.4-12.6 microns on Landsat 3	56x79 m (MSS)	185x185 km	18 days Over Equator at 09.30 hours
Operational: Landsat 4: 1982-date Landsat 5: 1984-date	705 km	MSS and Thematic Mapper (TM): 0.45-0.52; 0.52-0.60; 0.63-0.69; 0.76-0.90; 1.55-1.75; 2.08-2.35; 10.4-12.5 microns	30x30 m (TM)	185x185 km	16 days Over Equator at 09.30 hours
Planned: Landsat 6: 1993- Landsat 7: 1995/7-	705 km	Enhanced TM and high - resolution panchromatic (0.5-0.9 microns)	15x15 m (panchrom-atic)	185x185 km	
<u>METEOR (Russia)</u>	Polar 900 km	No information available			Equator 15.00 hours

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Satellite programme	Orbit type/height	Sensor types	Spatial resolution	Scene size	Temporal repetitivity
<u>METEOSAT</u> **<u>(Europe)</u>** Meteorological Satellite Meteosat 4 re-named Meteosat Operational Satellite (MOP-1)	Geo-stationary	Visible/infra-red			
Operational: Meteosat 2: 1981-date (back up) Meteosat 3: 1988-date (back up to GOES-7) Meteosat 4 (MOP 1): 1989-date Meteosat 5 (MOP 2):1991-date	36,000 km	Multispectral radiometer, 3 bands: 'visible', 0.4-1.1 microns 'water vapour', 5.7-7.1 microns 'thermal infra-red', 10.5-12.5 microns	2.5 km (visible) 5 km (water & thermal infra-red)	Limb to limb	30 minutes
Planned: Meteosat 6 (MOP 3):1993-		As above			
Second generation Meteosats in 1998		Planned 14 bands 0.6-14 microns			

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Satellite programme	Orbit type/height	Sensor types	Spatial resolution	Scene size	Temporal repetitivity
MOS 1 (Japan) Marine Observation Satellite	Polar	Visible/thermal infra-red/microwave			
Operational: MOS-1a: 1987-date MOS-1b: 1990-date	913 km	Multispectral electronic self-scanning radiometer (MESSR): 0.51-0.59; 0.64-0.72; 0.72-0.80; 0.80-1.1 microns	50x50 m (MESSR)	200x200 km	14 days
		Visible and thermal infrared radiometer (VTIR): 0.5-0.7; 6.0-7.0; 10.5-11.5; 11.5-12.5 microns	900x900 m(vis) 2700m (i.r.)	1500 km swath (vis)	
		Microwave scanning radiometer (MSR): 23.8 GHz	32 km	2700x2700 km	
		31 GHz	23 km		
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Satellite programme	Orbit type/height	Sensor types	Spatial resolution	Scene size	Temporal repetitivity
<u>NOAA (USA)</u> National Oceano-graphic and Atmospheric Administration Runs several series.	Polar	Visible/infra-red and others			
Operational:					
TIROS-N series NOAA 6&7: 1978-date	833km (two satellites at orbital separation of 90°)	Advanced Very High Resolution Radiometer (AVHRR), 5 bands: 0.58-0.68; 0.72-1.1; 3.55-3.93; 10.5-11.5; 11.5-12.5 microns <u>and</u> sounders, microwave scanners and vertical temperature profiling	1.1km local area coverage (LAC) 5 km global area coverage (GAC)	2700 km (typical)	12 hours Over Equator at 02.00, 07.30, 14.30 & 19.30 hours
Advanced TIROS-N series NOAA 8, 9, 10, 11: 1981-date	833km (two satellites at orbital separation of 90°)	AVHRR as per NOAA 6 & 7 Weekly vegetation index	1.1km LAC 4 km GAC	2700 km(typical)	12 hours Over Equator at 02.00, 07.30, 14.30 & 19.30 hours
Planned: NOAA-K: 1994 NOAA-L: 1996 NOAA-M: ?		As above	As above		

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Satellite programme	Orbit type/height	Sensor types	Spatial resolution	Scene size	Temporal repetitivity
Radarsat (Canada)	Polar	Visible/infra-red and microwave radar			24 days
Planned: 1994	798 km	AVHRR as on NOAAs and Multilinear Array Sensor (MSS) 0.45-0.50; 0.52-0.59; 0.62-0.68; 0.84-0.88 microns and Synthetic Aperture Radar (SAR): 5.3 GHz (C-band)	1300m (AVHRR) 30m (MSS) SAR: 28x25 m 28x35 m 10x10 m	3000 km swath 417 km swath 100 km swath 150 km swath 45 km swath	
SIR-C/X-SAR (USA) Shuttle Imaging Radar-C & X-band Synthetic Aperture Radar	Variable approx. Polar	Microwave radar and others			
Planned: 1993, 1994 & 1996, short shuttle flights	200-300 km (approx.)	SIR-C: 24 cm.(L-band) and 5.6 cm. (C-band) in many polarisation combinations. X-SAR: 3.1 cm (X-band) in VV polarisation	25m (20 MHz bandwidth) 40m(10 MHz bandwidth)	15-90 km swaths	Unknown

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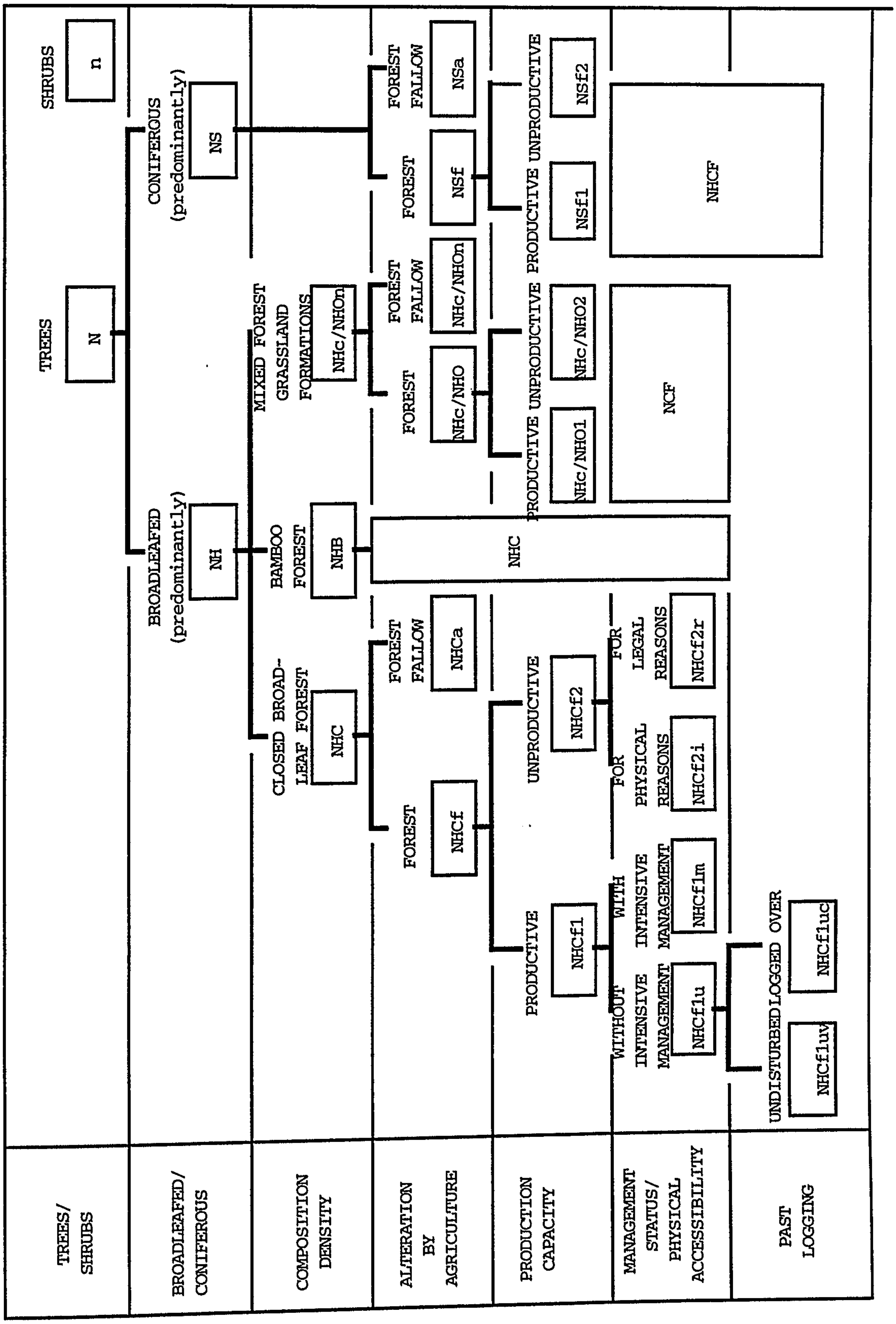
Satellite programme	Orbit type/height	Sensor types	Spatial resolution	Scene size	Temporal repetitivity
SPOT (France)	Polar	Visible/near infra-red			
Operational:					
Spot 1: 1986 date (partial cover) Spot 2: 1990-date	832 km	Two haute resolution visible (HRV) charge coupled device (CCD) detectors: 0.5-0.59; 0.61-0.68; 0.79-0.89 microns and panchromatic 0.51-0.73 microns	20x20 m (multi-spectral) 10x10 m (pan-chromatic)	60x60 km	26 days (down to 2.4 days on stereoviewing) Over Equator at 10.30 hours
Planned: Spot 3: 1993- Spot 4: 1994- Spot 5: 1999-		Two new HRV CCD detectors: 10x10 m panchromatic replaced with 10x10 m: 0.61-0.68 micron plus 1.5-1.7 micron at 20x20 m plus new low resolution sensor (1 km resolution)	20x20 m (multi-spectral) 10x10 m (pan-chromatic)	60x60 km	26 days (down to 1 day on low resolution) Over Equator at 10.30 hours
END OF TABLE					

Appendix 3: FAO Classification of natural woody vegetation.



For key to Classification index, see next page.

Key to FAO Classification of Vegetation Index

(Source of information: FAO Forestry Paper 30 (1982) Rome. 'Tropical Forest Resources.')

These are the main classes of forests in the FAO Inventory scheme. Distinctions are made between the various types of forest according, firstly to the predominant types of vegetation and, secondly, according to their usefulness for the purposes of development.

N: any vegetation type of which the dominant woody element is the tree, which is defined as "a woody perennial plant, typically large and with a single well defined stem carrying a more or less definite crown". (Height more than 7m for mature trees.)

n: any vegetation type the main elements of which are shrubs of more than 50 cm and less than 7m in height.

NH: Types with a predominance of trees of broadleafed species. predominance is characterised by a proportion of more than 50% of the crown cover.

NS: types with a predominance of trees of coniferous species.

NHC: closed broadleaved forests, i.e. those which, when not recently cleared for shifting agriculture or heavily exploited, cover with their various stories and undergrowth, a high proportion of the ground and do not have a continuous dense grass layer allowing grazing and the spreading of fires. They are often but not always multi-storied.

NHB: bamboo plantations.

NHc/NHO: mixed broadleaved forest-grassland and tree formations with a continuous dense grass layer in which the trees cover more than 10%.

NHCf: stands of closed broadleaved forest which have not been cleared in the recent past (20-30 years). These forests are either managed or unmanaged, primary or in an advanced state of reconstitution after having been cleared at least 60-80 years ago. The forests may have been logged-over one or more times, having kept their characteristics of forest stands, possibly with modified structure and composition.

NHCa: (forests fallow) all complexes of woody vegetation deriving from the clearing by shifting cultivation of closed broadleaved forests. Patches of uncleared forest and of agricultural fields are generally included within these areas as it is impossible to account for them separately within the shifting cultivation areas. When site conditions are unfavourable (e.g. broken terrain) or when the fallow period is reduced to a very short period, clearing by agriculture leads to such a degeneration of the site that reconstitution of the forest is not possible within a foreseeable future. the resulting degraded vegetation is then listed as shrub (n).

NHCf1: 'productive' closed broadleaved forests (managed or not), that due to their location and characteristics would be suitable for the production of wood for industrial purposes (sawlogs, veneers, pulpwood, pitprops etc).

NHCf2: 'unproductive' closed broadleaved forests, for reasons of location or general characteristics of the wood concerned.

NHc/ NHO: mixed broadleaved forest/grassland variations of forests (productive and unproductive).

Appendix 4: Overview of Remote Sensing Archive System

(From: IGBP report 20: "Improved Global Data for Land Applications", 1992.)

SITE NAME	SITE LOCATION	TYPE OF ACQUISITION			TYPE OF ARCHIVE			
		Satellite number	Overpass	Frequency	Data archived	Months retained	Open catalogue	Data retriev-able
Antarc-tica Syowa	Lat. 69 S Long. 39° 34'E	6-7 9-12	Daytime	Daily	Raw and Processed	Permanent	Yes	Yes
Antarc-tica Terranova Bay	Lat. 74°24'S Long. 164° 7'E	10-12	Day and Night	Daily	Raw	Permanent	Yes	Yes
Antarc-tica O'Higgins	Lat. 63° 19'S Long. 57°5 4'W	9-12	Daytime	Daily	Raw	Permanent	Yes	Yes
Antarc-tica Mc Murdo Station	Lat. 77° 51'S Long. 166° 40'E	6-11	Daytime	Daily	Raw	Permanent	Yes	Yes
Antarc-tica Palmer Station	Lat. 64°46'S Long. 64°4'W	6-11	Daytime	Daily	Raw	Permanent	Yes	Yes
Argentina Buenos Aires	Lat. 34° 24'S Long. 58° 18 'W	11	Daytime	Daily	Raw	Uncertain	Uncertain	Uncertain
Australia Alice Springs	Lat. 23° 45' S Long. 147° 18'E	10-12	Daytime	Daily	Raw	Permanent	Yes	Yes

Table continued on next page.

SITE NAME	SITE LOCATION	TYPE OF ACQUISITION			TYPE OF ARCHIVE			
		Satellite number	Overpass	Frequency	Data archived	Months retained	Open catalogue	Data retriev-able
Australia Hobart Tasmania	Lat. 420 48 'S Long. 147° 18' E	7-12	Day and Night	Daily	Raw	Permanent	Yes	Yes
Australia Aspen-dale	Lat. 36°S Long 145 °E	7-12		Daily	Raw	Permanent	Yes	Yes
Australia Perth	Lat. 32° S Long. 115° 53'E	7-12	Daytime	Daily	Raw	Permanent	Yes	Yes hard copy
Australia Towns-ville	Lat. 19° 18'S Long. 146° 18'E	9-12	Day and Night	Daily	Raw	12 months	Yes	Yes
Bangla-desh Dhakka	Lat. 23° 45'N Long. 90° 18'E	6-12	Day and Night	Daily	Raw	Permanent	No	No
Brazil Cachoeira Paulista	Lat. 22° 18'S Long. 45° W	9-12	Day and Night	Sporadic	Raw	Permanent	No	Yes
Canada Downs-view Ontario	Lat. 43° 46 'N Long. 79° 28' W	9-11	Daytime	Daily	Raw and Processed	10 years	Yes	Uncertain

Table continued on next page

SITE NAME	SITE LOCATION	TYPE OF ACQUISITION			TYPE OF ARCHIVE			
		Satellite number	Overpass	Frequency	Data archived	Months retained	Open catalogue	Data retriev-able
Canada Edmon-ton Alberta	Lat. 53° 30′N Long. 113° 30′	10 -11		Daily	Raw and Processed	10 days or 2 years hard copy	No	Unknown
Canada Prince Albert Saskat-chewan	Lat. 53° 12′ N Long. 105° 55′ W	6-12	Daytime	Daily	Raw	Permanent	Yes	Yes
Canary Islands Mas-polomas	Lat. 27° 46′N Long. 15°37′ W	9-12	Daytime	Daily	Raw	Permanent	Yes	Yes
Chile Santiago	Lat. 33°18′ S Long. 70° 24′W	7-12	Daytime	Daily	Raw	Permanent	Yes	No
Czechoslo vakia Prague	Lat. 50° 4′ N Long. 14° 27′E	6-12			Raw		Yes	Yes
France Lannion	Lat. 48° 45′N Long. 3°28 E	6-12	Day and Night	Sporadic	Raw and Processed	25 month rolling	Yes	Yes
Germany Berlin	Lat. 52° 28′N Long. 13° 12′E	6-11	Day and Night	Daily	Raw and Processed	Permanent	No	Yes

Table continued on next page.

SITE NAME	SITE LOCATION	TYPE OF ACQUISITION			TYPE OF ARCHIVE			
		Satellite number	Overpass	Frequency	Data archived	Months retained	Open catalogue	Data retriev-able
Germany Bremer-haven	Lat. 53°31'N Long. 8°34'E	9-12		Sporadic	Raw and Processed		No	Yes
Germany Hamburg	Lat. 53°34'N Long. 9°58'E	9-12		Daily	Raw		Yes	Uncertain
Germany Munich	Lat. 48°30'N Long. 11°9'E	6-12	Day and Night	Daily	Raw	Permanent	Yes	Yes
India Shad-nagar Hyder-abad	Lat. 17°7'N Long. 78°20'E	11	Day and Night	Daily	Raw	Permanent		
Italy Rome	Lat. 41°26'N Long. 12°14'E	9-12	Day and Night	Daily	Raw		No	No
Italy Scanzano	Lat. 37°54'N Long. 13°21'E	9-12		Daily	Raw		Yes	Uncertain
Indonesia Lapan	Lat. 6°5'N Long. 106°E	6-12	Daytime	Daily	Raw	Permanent	No	Yes

Table continued on next page.

SITE NAME	SITE LOCATION	TYPE OF ACQUISITION			TYPE OF ARCHIVE			
		Satellite number	Overpass	Frequency	Data archived	Months retained	Open catalogue	Data retriev-able
Japan Kiyose	Lat. 35°45'E Long. 139°31'E	6-12	Daytime	Daily	Raw and Processed	Permanent	Yes	Yes
Japan Tokyo (Tokai Univ.)	Lat. 32°49'N Long. 130°52'E	6-12	Daytime	Daily	Raw and Processed	Permanent	No	Yes
Japan Tokyo (Tokyo Univ.)	Lat. 36°N Long. 140°E	6-12	Daytime	Daily	Raw	Permanent	Yes	Yes
Japan Sendai	Lat. 38 deg 15'N Long. 140°50'E	9-12	Daytime	Daily	Raw and Processed	Permanent	Yes	Yes
Korea Seoul (KMS)	Lat. 37°36'N Long. 127°E	10-12	Day and Night	Daily	Processed	Permanent	Yes	Yes
Korea Seoul (Nat. Univ.)	Lat. 37°30'N Long. 127°E	9-12	Daytime	Daily	Raw	Permanent	Yes	Yes
La Reunion	Lat. 20°52'S Long. 55°28'E	9-12	Daytime	Daily	Raw	Permanent	Yes	Yes

Table continued on next page.

SITE NAME	SITE LOCATION	TYPE OF ACQUISITION			TYPE OF ARCHIVE			
		Satellite number	Overpass	Frequency	Data archived	Months retained	Open catalogue	Data retriev-able
Niger Niamey	Lat. 13°31'N Long. 2°4'E	10-12	Daytime	Daily	Raw and Processed	Permanent	Yes	Yes
Nether-lands de Bilt	Lat. 52°N Long. 5°E	6-12	Daytime	Daily	Processed	Permanent	Yes	Yes
New Zealand Welling-ton	Lat. 41°12'S Long. 174°30'E	10-12	Daytime	Daily	Processed Geo-located	Permanent	No	No
Norway Tromso	Lat. 69°39'N Long. 18°56'E	6-12	Day and Night	Daily	Raw	Permanent	Yes	Yes
Poland Krakow	Lat. 50°N Long. 20°E	9-12	Daytime	Daily	Raw	Permanent	No	Yes
South Africa Harten-easthoek	Lat. 25°53'S Long. 27°42'E	6-12	Day and Night	Daily	Raw	Permanent	Yes	Yes
Switzer-land Berne	Lat. 46°10'N Long. 6°E	6-12	Day and Night	Daily	Raw	Permanent	Yes	Yes
Taiwan Keelung	Lat. 25°7'N Long. 121°43'E	10-12	Day and Night	Daily	Raw	Permanent	No	Unknown

Table continued on next page.

SITE NAME	SITE LOCATION	TYPE OF ACQUISITION			TYPE OF ARCHIVE			
		Satellite number	Overpass	Frequency	Data archived	Months retained	Open catalogue	Data retriev-able
Taiwan Taipei	Lat. 25° N Long. 121° E	6-12	Day and Night	Daily	Raw	Permanent	No	No
United Kingdom Dundee	Lat. 56° 27'N Long. 2° 30'W	6-12	Day and Night	Daily	Raw	Permanent	Yes	Yes
United Kingdom Lasham	Lat. 51° 11'N Long. 1° 2'W	6-12	Day and Night	Daily	Raw	2 Weeks	No	No
USA Austin Texas	Lat. 30° 16'N Long. 97° 45'W	10, 11	Daytime	Daily	Raw	Permanent	Yes	Yes
USA Baton Rouge Louisiana	Lat. 30° 24'N Long. 91° 10'W	9, 10, 11	Day and Night	Daily	Raw	Permanent	Yes	Yes
USA Fairbanks Alaska	Lat. 64° 56'N Long. 147° 30'W	6-11	Day and Night	Daily	Raw	Permanent	Yes	Yes

Table continued on next page.

SITE NAME	SITE LOCATION	TYPE OF ACQUISITION			TYPE OF ARCHIVE			
		Satellite number	Overpass	Frequency	Data archived	Months retained	Open catalogue	Data retriev-able
USA Uhsnug Harbour Hawaii	Lat. 21° 19'N Long. 157° 15'W	9-11		Daily	Processed	12 months on-line SST to CD	Yes	Yes
USA Sioux Falls South Dakota	Lat. 43° 32'N Long. 96° 44'W	9-11	Daytime	Daily	Raw	Permanent	Yes	Yes
USA Stennis Space Center MS	Lat. 30° 12 'N Long. 89° 33 'W	10 -11		Sporadic	Processed	12 months	Yes	Yes
USA Wallops Island Virginia	Lat. 37° 52'N Long. 75° 27'W	6-11	Day and Night	Daily	Raw	Permanent	Yes	Yes

End of Table.

Appendix 5: UK Forestry Commission Tree Census Sites

(From: 'Remote sensing and Image Interpretation', T.M. Lillesand and R.W. Kiefer, (eds.), 2nd edition, Wiley, 1987.)

Figure 1. Location of plots used in the 1990 programme.

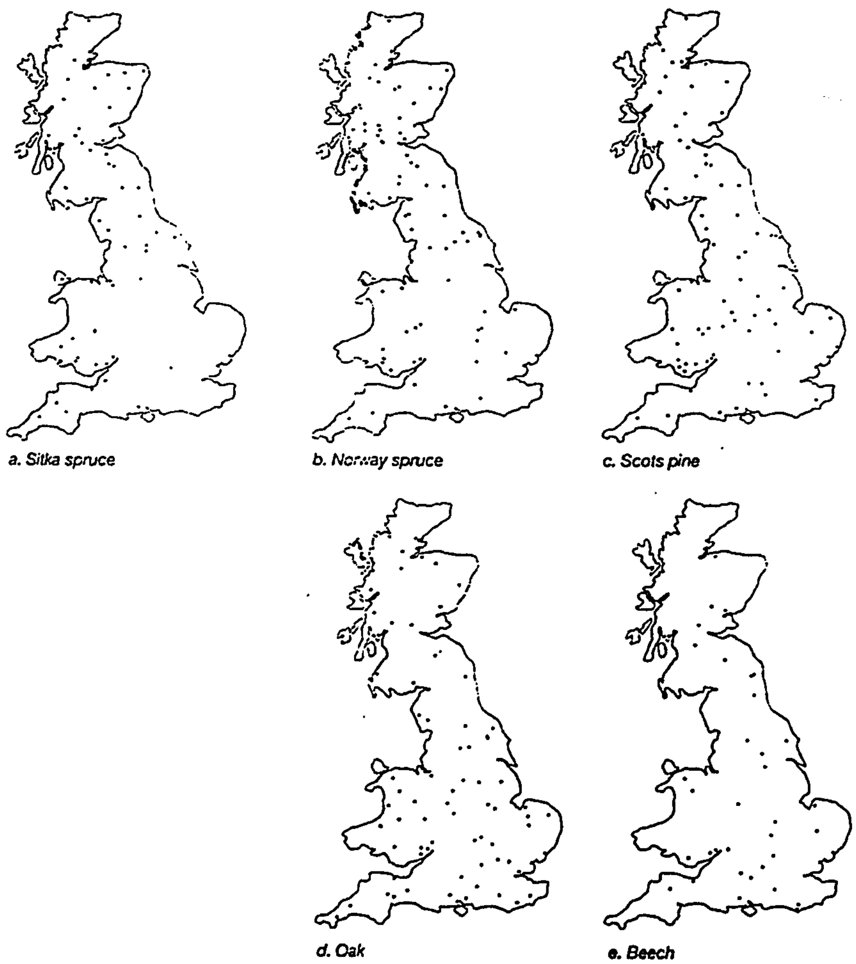


Figure 2. Loss of branches from an oak during the period 1987 to 1990.

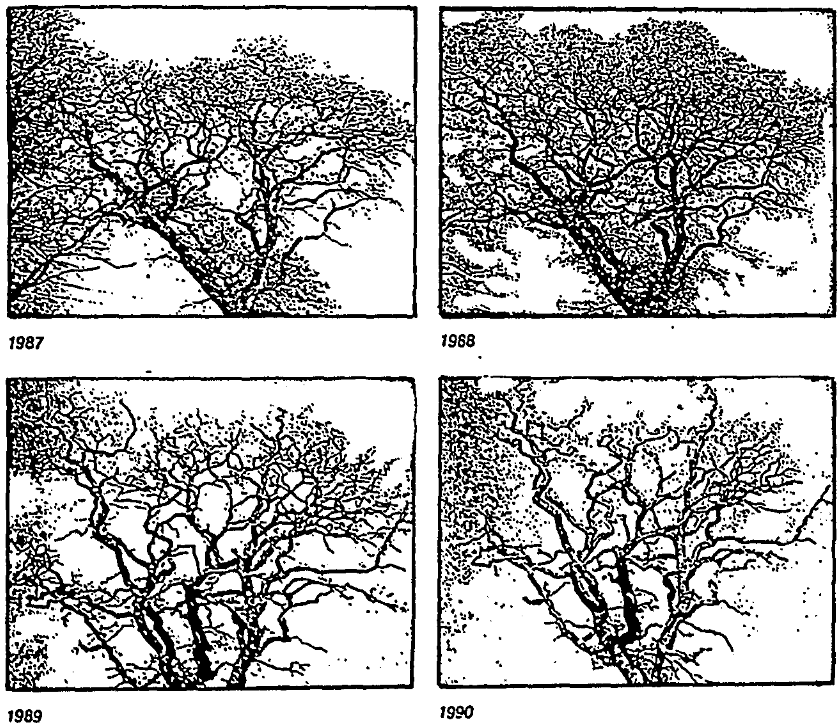


Table 1. Indices assessed in the 1990 U.K. Programme

Variable	Sitka spruce	Norway spruce	Scots pine	Oak	Beech
Branch density	×	×	×		
Branch pattern	×	×			
Browning of current needles	×	×	×		
Browning of leaves				×	×
Browning of older needles	×	×	×		
Butt damage	×	×	×	×	×
Canopy closure around tree	×	×	×	×	×
Crown density	×	×	×	×	×
Crown dieback extent				×	×
Crown dieback location				×	×
Crown dieback type				×	×
Crown form			×	×	×
Diameter at breast height	×	×	×	×	×
Defoliation type	×	×	×	×	×
Degree of leaf rolling					×
Epicormics on branches				×	

Table 1. continued

Variable	Sitka spruce	Norway spruce	Scots pine	Oak	Beech
Epicormics on stem				×	
Flowering in lower crown			×		
Flowering in upper crown			×		
Frequency of leaf rolling					×
Fruiting	×	×	×	×	×
Fungal presence	×	×	×	×	×
Insect damage	×	×	×	×	×
Leader condition	×	×	×		
Leaf size					×
Mechanical damage to crown	×	×	×	×	×
Needle retention	×	×	×		
Overall discoloration	×	×	×	×	×
Premature leaf loss					×
Secondary shoot frequency	×	×			
Secondary shoot location	×	×			

Table 1. continued

Variable	Sitka spruce	Norway spruce	Scots pine	Oak	Beech
Shoot death extent	×	×	×		
Shoot death location	×	×	×		
Stem damage	×	×	×	×	×
Tree dominance	×	×	×	×	×
Type of leaf browning				×	×
Type of leaf yellowing				×	×
Type of needle yellowing	×	×	×		
Yellowing of current needles	×	×	×		
Yellowing of leaves				×	×
Yellowing of older needles	×	×	×		

Table 2. Data completeness expressed as percentage of the total number of records that should have been collected

Variable	Sitka spruce	Norway spruce	Scots pine	Oak	Beech
Branch density	98	99	100		
Branch pattern	98	99			
Browning of current needles	98	99	98		
Browning of leaves				99	100
Browning of older needles	98	99	100		
Butt damage	98	99	100	98	100
Canopy closure around tree	98	99	100	98	100
Crown density	98	99	100	98	100
Crown dieback extent				98	5
Crown dieback location				98	100
Crown dieback type				98	100
Crown form			100	98	100
Diameter at breast height	98	99	100	98	100
Defoliation type	98	99	100	98	100
Degree of leaf rolling					100
Epicormics on branches				98	

Table 2. continued.

Variable	Sitka spruce	Norway spruce	Scots pine	Oak	Beech
Epicormics on stem				98	
Flowering in lower crown			100		
Flowering in upper crown			100		
Frequency of leaf rolling					100
Fruiting	98	99	100	98	100
Fungal presence	98	99	100	98	100
Insect damage	98	99	100	98	100
Leader condition	98	98	100		
Leaf size					100
Mechanical damage to crown	98	99	100	98	100
Needle retention	98	99	100		
Overall discoloration	98	99	100	98	100
Premature leaf loss					100
Secondary shoot frequency	98	99			
Secondary shoot location	98	99			
Shoot death extent	98	99	100		

Table 2. continued

Variable	Sitka spruce	Norway spruce	Scots pine	Oak	Beech
Shoot death location	98	99	100		
Stem damage	98	99	100	98	100
Tree dominance	98	99	100	98	100
Type of leaf browning				98	100
Type of leaf yellowing				98	100
Type of needle yellowing	98	99	100		
Yellowing of current needles	98	99	100		
Yellowing of leaves				98	100
Yellowing of older needles	98	99	100		

Table 3. Reliability of Sitka spruce data

(As indicated by comparisons between the surveyors' and the check teams' scores. Sample size 71. Tests not used on number differences less than 3.)

Variable	Number different	t-test	Wilcoxon test		Standard deviation
			T	Z	
Dominance	6		10.5	0	1.000
Canopy closure	17		51.0	1.21	0.230
Branch pattern	8		11.0	0.98	0.329
Defoliation type	10		18.5	0.92	0.361
Crown density	6	1.653			0.103
Shoot death location	16		50.0	0.93	0.354
Shoot death extent	13		4.0	2.90	0.004
Secondary shoots location	12		5.5	2.63	0.008
Secondary shoots abundance	9		18.0	0.53	0.595
Leader condition	2				
Coring	1				
Branch density	12		0.0	3.06	0.002
Needle retention	1				
Browning of current needles	0				
Browning of older needles	0				
Yellowing of current needles	3		1.5	0.80	0.424
Current yellowing type	0				
Yellowing of older needles	3		2.0	0.54	0.594

Table 3. continued.

Variable	Number different	t-test	Wilcoxon test T	Z	Standard deviation
Older yellowing type	2				
Overall discoloration	4		5.0	0.0	1.000
Mechanical damage type	5		0.0	2.02	0.043
Mechanical damage type (%)	5	-1.943			0.056
Stem damage type	1				
Stem damage (%)	0				
Insect activity	11		7.0	2.31	0.021
Fungi	0				

Appendix 6: Tree Outlines and Airborne Identification Methods

(From: 'Remote sensing and Image Interpretation', T.M. Lillesand and R.W. Kiefer, (eds.), 2nd edition, Wiley, 1987.)

Figure 1. Silhouettes of forest trees (American Society of Photogrammetry)

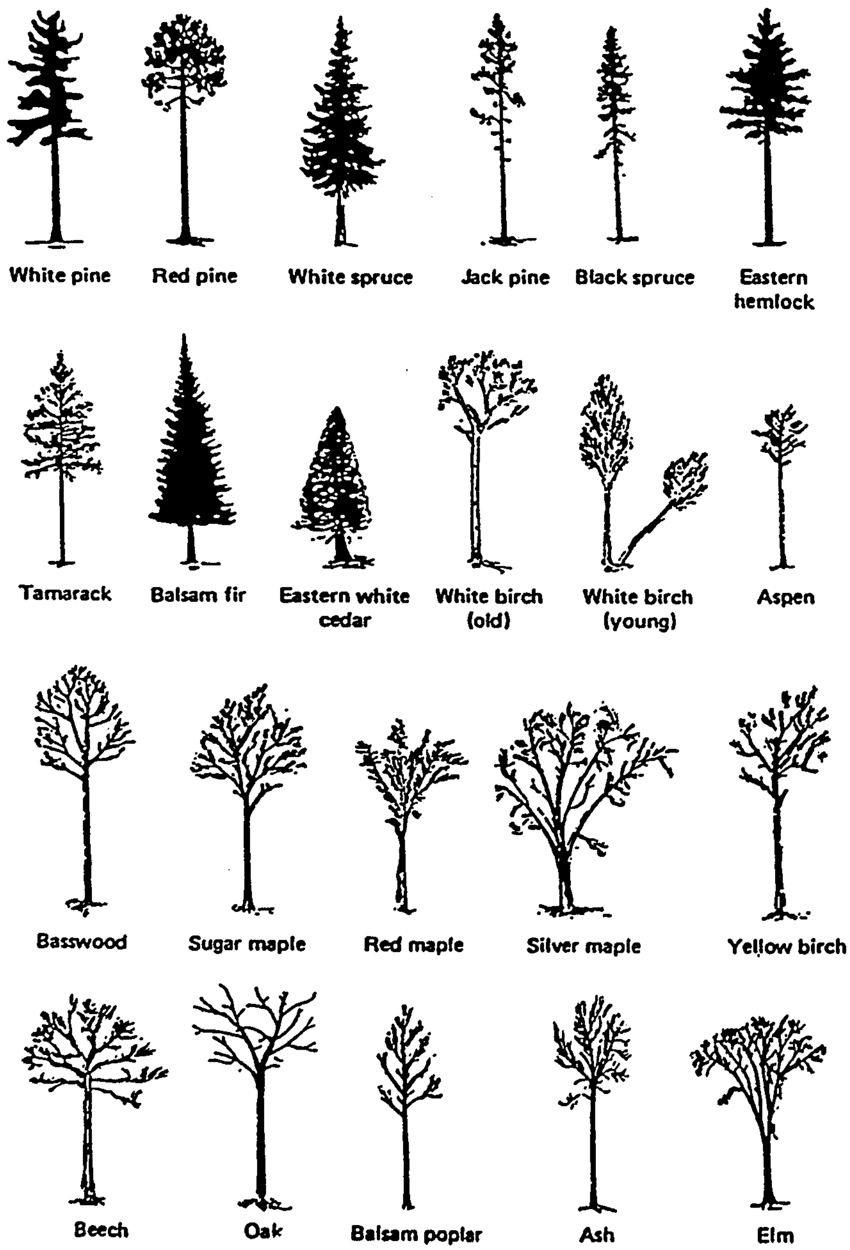


Figure 2. Aerial views of tree crowns - most trees are shown with radial displacement (American Society of Photogrammetry).

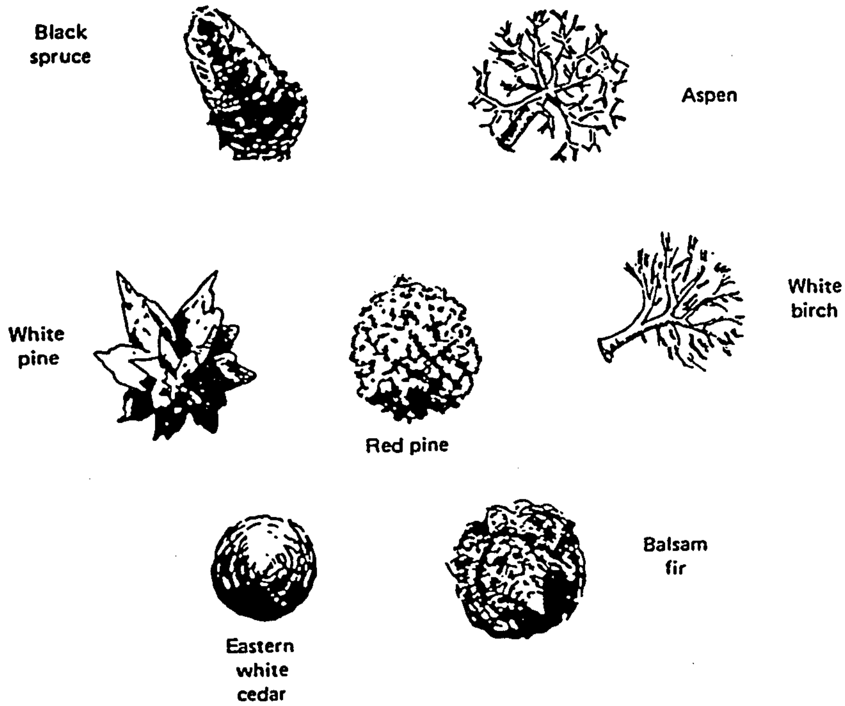


Table 1. Airphoto Interpretation Key for the Identification of Hardwoods in Summer

1. Crowns compact, dense and large:	
2 Crowns very symmetrical and very smooth, oblong or oval; trees form small portion of stand.	Basswood
2. Crowns irregularly rounded (sometimes symmetrical), billowy and tufted.	
3. Surface of crown not smooth but billowy.	Oak
3. Crowns rounded, sometimes symmetrical, smooth surfaced.	Sugar maple, beach
3. Crowns irregularly rounded or tufted.	Yellow birch
1. Crowns small, or if large, open or multiple.	
6. Crowns small, or if large, open and irregular, revealing light coloured trunk.	
7. Trunk chalk white, often forked, trees tend to grow in clumps.	White birch
7. Trunk light but not white, undivided trunk reaching high into crown, generally not in clumps.	Aspen
6. Crown medium sized or large; trunk dark.	
8. Crown tufted, or narrow and pointed.	
9. Trunk often divides, crown tufted.	Red maple
9. Undivided trunk, narrow crown.	Balsam poplar
8. Crown flat topped or rounded.	
10. Crowns medium sized, rounded; undivided trunk; branches ascending.	Ash
10. Crowns large, wide; trunk divided into big spreading branches.	
11. Top of crown appears pitted.	Elm
11. Top of crown closed.	Silver maple

Table 2. Airphoto Interpretation Key for the identification of Conifers

1. Crowns small, or if large, then definitely cone shaped.	
Crowns broadly conical, usually rounded tip; branches not prominent.	Cedar
Crowns narrow, often cylindrical, trees frequently grow in swamps.	Swamp black spruce
Crowns conical, deciduous, very light toned in fall, usually associated with black spruce.	Tamarack
Crowns narrowly conical, very symmetrical, top pointed, branches less prominent than in white spruce.	Balsam fir
Crowns narrowly conical, top often appears obtuse on photograph (except northern white spruce); branches more prominent than in balsam fir.	White spruce Black spruce
Crowns irregular, sometimes with pointed top; have thinner foliage and smoother texture than spruce and balsam fir.	Jack pine
1. Crowns large and spreading, not narrowly conical; top often not well defined.	
2. Crowns very dense, irregular or broadly conical.	
Individual branches very prominent; crown usually irregular.	White pine
Individual branches rarely prominent; crown usually conical.	Eastern hemlock
2. Crowns open, oval (circular in plan view).	Red pine

Appendix 7: The CORINE Geographic Information System

(From: 'Geographic Information Systems and Environmental Problems', D. Rhind, Global Environmental Change, pp 649-668, November 1991.)

Table 1. Overview and Contents of the CORINE Geographic Information System

Theme	Nature of the information	Characteristics of digital data	Quantity of data (Mbytes)	Resolution or scale
Biotypes	Location and description of biotypes of major importance for nature conservation in the Community	5,600 biotypes described on about 20 characteristics. Boundaries of 440 biotypes in Belgium and Portugal	20.0 2.0	Location of the centre of the site
Designated areas	Location and description of areas classified under various types of protection	13,000 areas with 11 attributes. Computerised boundaries of areas designated in compliance with article 4 of EEC/409/79 directive on the conservation of wild birds	6.5	Location of the centre of the site 1/100,000
Emissions into the air	Tons of pollutants (SO_2,, NO_x, VOC emitted per source category,: power stations, industry, transport, nature, oil refineries, combustion	1 value per pollutant, per category of source and per region, plus data for 1400 point sources i.e. ±200,000 values in total	2.5	Regional (NUTS III[7]) and location of large emission sources
Water resources	Location of gauging station, drainage basin, mean and minimum discharge 1970-85 for Southern part of EEC	Data recorded for 1061 gauging stations for 12 variables	3.2	Location of gauging stations
Coastal erosion	Morpho-sedimentological characteristics (4 categories) presence of constructions, coastal evolution characteristics, erosion, accretion, stability	17,500 coastal segments described	25.0	Base file 1/100,000. Generalised version 1/1,000,000

7 NUTS is the Nomenclature of Territorial Units for Statistics

Table 1. Continued

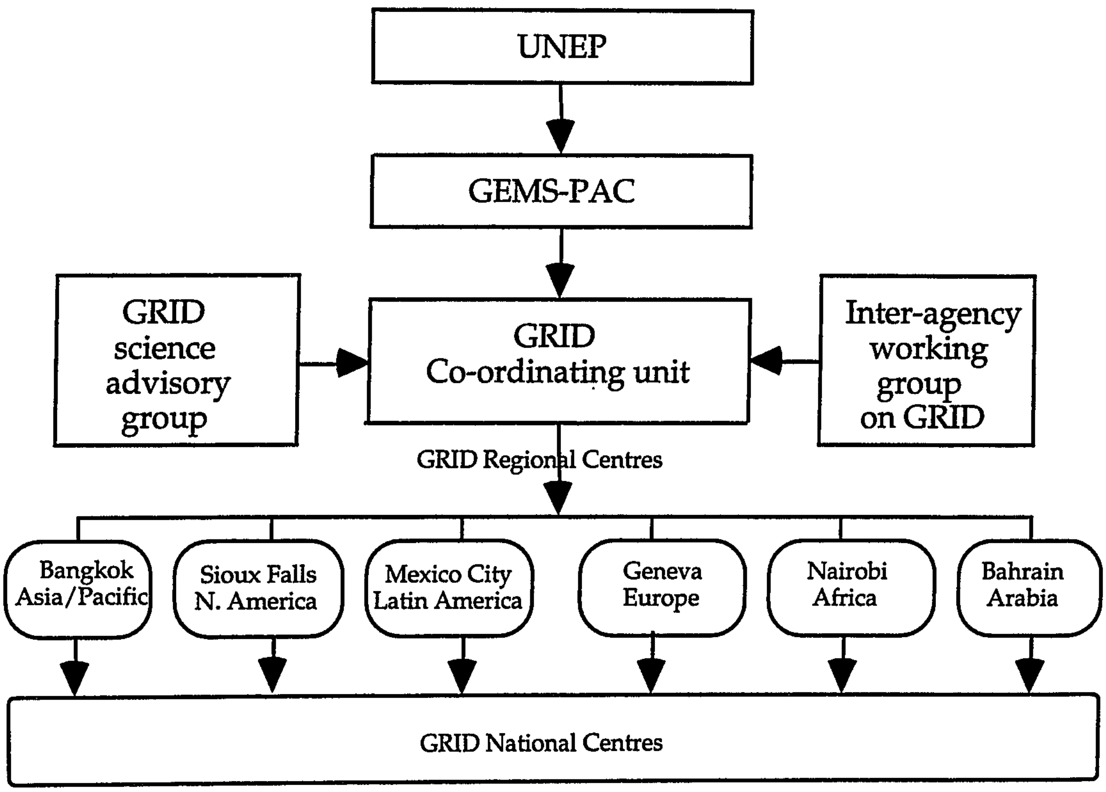
Theme	Nature of the information	Characteristics of digital data	Quantity of data (Mbytes)	Resolution or scale
Soil erosion risk	Assessment of potential and actual soil erosion risk by combining 4 sets of factors: soil, climate, slopes, vegetation	180,000 homogeneous areas (southern part of the Community)	400.0	1/1,000,000
Important land resources	Assessment of land quality by combining 4 sets of factors: soil climate slopes, land improvements	170,000 homogeneous areas (southern part of Community)	300.0	1/1,000,000
Natural potential vegetation	Mapping of 140 classes of potential vegetation	2288 homogeneous areas	2.0	1/3,000,000
Land cover	Inventory of biophysical land cover in 44 classes	Vectorised database for Portugal and Luxembourg	51.0	1/100,000
Water pattern	Navigability, categories (rivers, canals, lakes, reservoirs)	49,151 digitised river segments	13.8 0.3	1/1,000,000 1/3,000,000
Bathing water quality	Annual values for up to 18 parameters, 113 stations for 1976-86, supplied in compliance with EEC/76/160 directive	2650 values	0.2	Location of stations
Soil types	320 soil classes mapped	15,498 homogeneous areas	9.8	1/1,000,000
Climate	Precipitation and temperature (+ incomplete data for other variables)	Mean monthly values for 4,773 stations	7.4	Location of station
Slopes	Mean slope per square km (southern regions of the Community)	1 value per km^2 i.e. 800,000 values	150.0	1/100,000
Administrative units	EC NUTS: 4 hierarchical levels	470 NUTS digitised	0.7	1/3,000,000

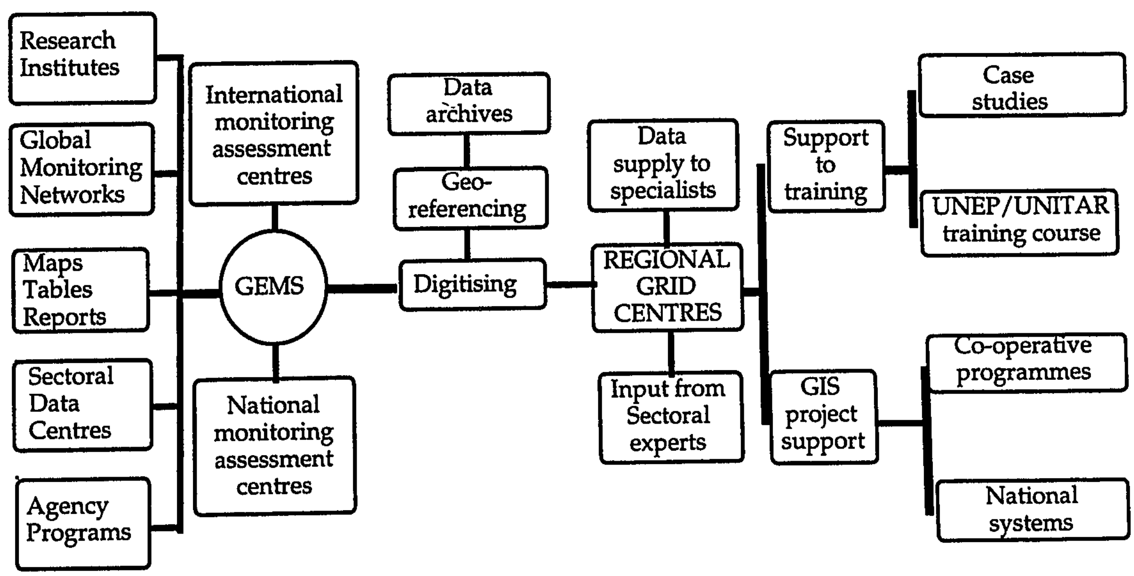
Table 1. Continued

Theme	Nature of the information	Characteristics of digital data	Quantity of data (Mbytes)	Resolution or scale
Coasts and countries	Coastline and national boundaries (Community and adjacent territories)	62,734 km	0.3 3.2	1/3,000,000 1/1,000,000
Coasts and Countries	Coastline and boundaries (planet)	196 countries	1.5	1/25,000,000
ERDF regions	Eligibility for Structural Funds	309 regions classified	0.01	Eligible regions
Settlements	Name, location, population of urban centres >20,000 people	1542 urban centres	0.1	Location of centres
Socio-economic data	Statistical series extracted from the SOEC-REGIO database	Population, transport agriculture, etc.	40.0	Statistical Units NUTS 111
Air traffic	Name, location of airports, type and volume of traffic	254 airports	0.1	Location of airports
Nuclear power stations	Capacity, type of reactor, energy production	97 stations, up-date 1985	0.03	Location of station

Appendix 8: The GRID Organisation and Structure

(From: GRID, Nairobi)





Appendix 9: The United States Geological Survey Land Use Classification System

Table 1. The USGS Land Use Land Cover Classification System for use with Remote Sensor Data

Level I	Level II
1 Urban or built-up land	11 Residential
	12 Commercial and Service
	13 Industrial
	14 Transport, communications and utilities
	15 Industrial and commercial complexes
	16 Mixed urban or built-up land
	17 Other urban or built-up land
2 Agricultural land	21 Cropland and pasture
	22 Orchards, groves, vineyards, nurseries and ornamental horticultural areas
	23 Confined feeding operations
	24 Other agricultural land
3 Rangeland	31 Herbaceous rangeland
	32 Shrub and bush rangeland
	33 Mixed rangeland
4 Forest land	41 Deciduous forest land
	42 Evergreen forest land
	43 Mixed forest land

Table 1. Continued

Level I	Level II
5 Water	51 Streams and canals
	52 Lakes
	53 Reservoirs
	54 Bays and estuaries
6 Wetland	61 Forested wetland
	62 Nonforested wetland
7 Barren land	71 Dry salt flats
	72 Beaches
	73 Sandy areas other than beaches
	74 Bare exposed rock
	75 Strip mines quarries and gravel pits
	76 Transitional areas
	77 Mixed barren land
8 Tundra	81 Shrub and brush tundra
	82 Herbaceous tundra
	83 Bare ground tundra
	84 Wet tundra
	85 Mixed tundra
9 Perennial snow or ice	92 Perennial snowfields
	92 Glaciers

Appendix 10: AVHRR land cover data sets

(From: IGPB report 20, 'Improved Global Data for Land Applications.')

Table 1. AVHRR land cover data sets: current and future availability*

Name of Data Set	Agency	Spatial Resolution **	Coverage	Availability
Global Vegetation Index (GVI)	NOAA	15-20 km	Global	1982 - present
Diskette Project	NCAAR	15-20 km	Africa Global	1982-98 ***
Modified GVI	UMCP	15-20 km	Global	1988- (Future 1982-90)
GIMMS Product	NASA/GSFC	7-8 km	Africa N. America S. America Asia Australia Europe	1982-90 *** *** *** *** ***
Land Pathfinder	NASA/NOAA (by 1994)	9 km	Global	1982-present
TREES	CEC/ISPRA	1.1 km and 4 km	Tropics	***
1 km product	USGS/EROS	1.1 km	USA	***
1 km sharp product	CEC/ISPRA	1.1 km	Europe	***

* Archives of AVHRR data requiring substantial processing before usage are not included.

** In this context spatial resolution refers to the bin or pixel size of the product.

*** Information not available.

Appendix 11: Acronyms

AMSU	Advanced Microwave Sounding Unit
ATSR-2	Along Track Scanning Radiometer-2
AVHRR	Advanced Very High Resolution Radiometer
BAHC	Biosphere Aspects of the Hydrological Cycle
CCRS	Canada Centre for Remote Sensing
CDA	Command and Data Acquisition
CEC	Commission of the European Community
CEOS	Committee for Earth Observation Satellites
CEOS	Committee on Earth Observation Satellites
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DIS	Data and Information System
DN	Digital Number
DOMSAT	Domestic Communications Satellite
DVI	Difference Vegetation Index
EDC	EROS Data Center
EOS	Earth Observing System
EPO	Earthnet Programme Office
EROS	Earth Resources Observing Satellite
ERS	European Remote Sensing satellite
ESA	European Space Agency
FAO	Food and Agriculture Organisation
GAC	Global Area Coverage

GAIM	Global Analysis Interpretation and Modelling (IGBP)
GARP	Global Atmospheric Research Programme
GCM	General Circulation Model
GCOS	Global Climate Observing System
GCTE	Global Change and Terrestrial Ecosystems (IGBP)
GIMMS	Global Inventory Monitoring and Modelling Studies
GSFC	Goddard Space Flight Centre
GVI	Global Vegetation Index
HRPT	High Resolution Picture Transmission
HRV	Haute Resolution Visible
ICSU	International Council of Scientific Unions
IFOV	Instantaneous Field of View
IGAC	International Global Atmospheric Project
IGBP	International Geosphere-Biosphere Project
IPB	Interactive Processing Branch
IR (or i.r.)	Infra-Red
ISCCP	International Satellite Cloud Climatology Project
ISLCP	International Satellite Land Surface Climatology Project
JRC	Joint Research Center
LAC	Local Area Coverage
LANDSAT	Land Remote Sensing Satellite
LERTS	Laboratoire d'Etudes et de la Recherche Télédétection Spatiale
LUT	Look-up Table
MERIS	European Medium Resolution Imaging Spectrometer

MODIS	Moderate Resolution Imaging Spectrometer
MSS	Multispectral Scanner System
MTV	Monitoring Tropical Vegetation
NAS	National Academy of Sciences (USA)
NASA	National Aeronautics and Space Administration (USA)
NCAR	National Centre for Atmospheric Research
NDVI	National Difference Vegetation Index
NESDIS	National Environmental Satellite Data and Information Service (USA)
NIR	Near infra-red
NOAA	National Oceanic and Atmospheric Administration
NPP	Net Primary Productivity
NRC	National Research Council (USA)
SAFISY	Space Agency Forum for the International Space Year
SMMR	Scanning Multifrequency Microwave Radiometer
SOCC	Satellite Operations Control Center
SPOT	Systeme pour l'Observation de la Terre
TM	Thematic Mapper
TOGA	Tropical Oceans and Global Atmosphere programme
TREES	Tropical Ecosystem Environment Observations by Satellite
USGS	United States Geological Survey
WDC	World Data Centre

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