BGD/84/056

INTEGRATED RESOURCE DEVELOPMENT OF THE SUNDARBANS RESERVED FOREST

BANGLADESH

FINAL REPORT OF THE MANGROVE INVENTORY CONSULTANT

by

J W Leech

United Nations Development Programme

Food and Agriculture Organization of the United Nations
Khulna, Peoples Republic of Bangladesh, April 1995

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This technical report is one of a series of reports prepared during the course of the project BGD/84/056. The conclusions and recommendations given in the report are those considered appropriate at the time of its preparation. They may be modified in the light of further knowledge gained at subsequent stages of the project.

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ABSTRACT

This reports on a total of four very short two week missions by the Mangrove Inventory Consultant to Project BGD/84/056, ranging from July 1994 to April 1995. It builds on earlier reports including the report of the second mission which was technically cleared by Rome in a Memo from P.Tesha, Chief, Forestry Operations Service (9/2/95 DP 9/7).

Earlier reports detailed the tasks that had to be carried out in order that the required information could be provided for the Integrated Resource Management Plan for the Sundarbans Reserved Forest. This activity was only activated late in the project life cycle and there was insufficient time to carry out the large number of field measurements that are really necessary in order to provide sound forest resource information. There was even less time available for data analysis. Therefore it was necessary to define a minimum set of tasks that would provide the best possible set of information to assist planning, given the tight time schedule. Progress has been considerable and is still ongoing. However the information that is desirable for good forest resource statistics cannot be obtained. In spite of the difficulties data were collected, some essential models were developed, and these are being, and will continue to be, summarised for inclusion in the IRMP.

The longer term information needs for effective management in the Sundarbans are addressed in the latter sections of this report. The current project is necessarily rather limited in its ability to provide all the information, but an integrated approach to total data collection is suggested that it is believed will, if fully implemented, be able to meet the future needs of the Forest Department.

RECOMMENDATIONS

The following recommendations are made after a series of discussions with the Officer in Charge Mr Peter de Vere Moss, other FAO Consultants, Experts and Specialists of the Project, and concerned counterparts and officials of the Forest Department. The forest plot remeasurement component was commenced only in April 1994 and there has been insufficient time or staff available to properly address the real requirement to provide sound forest resource information for inclusion into the IRMP (Integrated Resource Management Plan) for the Sundarbans.

A number of these recommendations will not be able to be implemented during the limited time remaining before project termination. However they are included to assist any ongoing relevant activities that may occur.

The recommendations are grouped by subject and are not in priority.

Permanent Sample Plot Data Base

1 It is strongly recommended that the efforts be made to continue the measurement of all the remaining PSP sites that have not yet been remeasured in 1994/95, even though analysis of these extra data may have to wait until after the preparation of the IRMP. To avoid the possibility of introducing a significant bias in the calculations it is highly desirable to measure all available plots and that they all be used to estimate the resource information.

It is also strongly recommended that all 120 PSP's be remeasured in the future as they will provide a sound data base for growth model development.

2 When opportunity permits some PSP's should be remeasured to provide control validation and enable a precision estimate to be made.

Felled Tree Volume Measurements

3 It is suggested that, when opportunity permits, felled tree volume measurements be collected from species other than Sundri and Gewa to either determine whether the previously used tree volume equations are appropriate or to develop new equations. It would be desirable to have more data for Sundri and Gewa from other sites.

Integrated Planning System

4 It is recommended that all PSP work, and any future TSP work, should be integrated into the data base structure established by the Project. This will facilitate the continued development of the IRMP for the Sundarbans, both before and after the Project is completed.

5 It is recommended that the any follow up project consider acquiring a PC based Image Processing capability. A system such as LARST (from the Natural Resources Institute ODA) can provide access to local satellite reception and relatively simple processing of that data. This would complement a system such as MicroBrian which would utilise

other commercially available imagery such as from Landsat TM and SPOT. It would also be highly desirable to acquire a good raster-vector analysis system such as Tydac's Spans. These acquisitions are not necessary for the current project but will be highly desirable for the ultimate implementation of an ongoing forest monitoring system for the SRF, perhaps through the planned Operational Unit (OU).

6 It is recommended that the Geographic Information System implemented by the project be strengthened so that it can continue to provide the spatial information necessary for integrated management planning in the Sundarbans.

These recommendations for continued development of the Integrated Planning System should be the function of the Operational Unit (OPSUNIT). This has been developed by the project and its ongoing implementation is under consideration.

Model Development

There are a number of models that should be developed using the PSP data in order to improve the precision of the resource calculations that can be incorporated into the IRMP and to provide mensurational tools that might be used by planners in the future.

7 It is recommended that, if the opportunity occurs, the tree volume equations development detailed in the Appendices 3 and 4 be extended to develop prediction equations for the following dependent variables:

- total stem volume over bark,
- total stem volume under bark,
- volume from stump to bole height under bark,
- volume from stump to bole height or 10 cm top diameter whichever is the lower point, over bark,
- as above, under bark,
- volume from ground to various top diameter limits,
- stump volume.

8 It is recommended that, if the opportunity occurs, equations be developed using mixed tree and stand variables to predict diameter growth by species for any site. This will provide the basis for a simple growth model.

Model Integration

9 It is desirable to extend the procedures developed by the Computer Programmer to incorporate the new statistical models as they are derived. The procedures must be maintained and will need to be modified as the preparation of the IRMP proceeds towards completion.

Future Monitoring

10 It is strongly recommended that the Forest Department consider changing from a stratified random sampling methodology to a systematic sample and consider adopting a continuing inventory of the forest rather than carrying out single stand alone estimates. The difficulty in obtaining a satisfactory stratification of the Sundarbans, the knowledge that this is continually changing, and changing quite rapidly, the need to

continually supply up to date planning information, the lack of knowledge about the unofficial felling of trees, the Sundri top-dying problem, and the advantages of being able to better interface with the newer technologies such as GIS, make such a change to a post sampling stratification seem the only satisfactory alternative.

Determination of Annual Allowable Cut

11 It is recommended that the Forest Department use a volume control methodology for setting the annual allowable cut (AAC) from the Sundarbans rather than basing allowable cut on area control. Further, it is recommended that a simulation model be used to determine the effect a range of particular levels of cut might have on the growing stock estimates, thus enabling computer sensitivity analyses to be carried out and the results used to assist the Department in setting an appropriate level of cut.

Miscellaneous

12 It is recommended that checks be made to ensure that only obviously unhealthy or unthrifty Sundri trees are removed in salvage felling operations. Salvage should not be used as an excuse for removing healthy trees damaged by cyclonic winds unless these are unlikely to recover.

13 It is recommended that a Golpatta Inventory be carried out in order to be able to determine the resource availability for the future. The lack of Goran information is also of concern. These can both best be addressed by implementation of the Temporary Sample Plot (TSP) system.

KEY WORDS

The following list of key words and phrases is provided as recommended (FAO 1994) to facilitate library searching and extraction of the document, primarily by the FAO Library and Documentation Systems Division (GIL).

Forest Inventory
Forest Management Planning
Forest Planning Systems
Geographic Information Systems (GIS)
Gewa
Golpatta
Goran
Integrated Data Base
Integrated Management Planning
Inventory
Mangrove Inventory
Mangrove Forest Management
Mangrove Forest Planning
Multiple Use Planning
Permanent Sample Plots
Sundri
Temporary Sample Plots
Tree Volume Equations

ACRONYMS

The following lists the acronyms that have been used in this report and also some that are included in other relevant documents.

AAC	Annual Allowable Cut
ASCII	American Standard Code for the Interchange of Information
AVHRR	Advanced Very High Resolution Radiometer, from NOAA
BGD	Bangladesh
BIT	Binary Digit, the minimum piece of computer information
BPI	Bits per inch, the packing density of computer tape
BYTE	A group of 8 bits
CCD	Charged Couple Device, a detector in multispectral scanners
CCF	Chief Conservator of Forests
CPR	Peoples Republic of China
DFD	Data Flow Diagram
DOS	Disc Operating System, for PC's
EOD	Entry On Date (date of entry of staff to the project)
ESRI	Environmental Systems Research Institute, the company that provided the Arc/Info GIS
FAO	The Food and Agriculture Organization of the United Nations.
FD	Forest Department of Bangladesh, or, Field Document
FORTRAN	Formula Translator, a computer compiler used to process some programs to be used in the IDB.
FRMP	Forest Resource Management Plan
GCP	Ground Control Point
GIS	Geographic Information System
GPS	Global Positioning System
IBM	International Business Machines

IDB	Integrated Data Base prepared for BGD/84/056
IR	Infrared
IRMP	Integrated Resource Management Plan for the SRF, to be prepared by BGD/84/056
ITTO	International Tropical Timber Organisation
KNM	Khulna Newsprint Mill Ltd.
LANDSAT	A series of satellites launched by NASA
LANDSAT TM	LANDSAT, Thematic Mapper
LANDSAT MSS	LANDSAT, Multi Spectral Scanner
LARST	Local Application of Remote Sensing Techniques
MSDOS	MicroSoft Disc Operating System for IBM compatible PC's
MSS	Multi Spectral Scanner
MSY	Maximum Sustainable/Sustained Yield
NASA	National Aeronautics and Space Administration of the United States of America
NOAA	National Oceanic and Atmospheric Administration of the United States of America
NPD	National Project Director
NTE	Not To Exceed (the date past which staff cannot be extended)
ODA	Overseas Development Administration
OS2	Operating System 2, for IBM based PC's
OPSUNIT	Operational Unit
PC	Personal Computer, generally IBM compatible
PIXEL	Derived from Picture Element, the smallest sample of an image having both spatial and spectral aspects
PSP	Permanent Sample Plot
RADAR	Radio Detection and Ranging
RIMS	Resource Inventory Management System
RS	Remote Sensing

SML	Small Macro Language, a version of AML (Arc Macro Language) the programming language used in ESRI's Arc/Info GIS to prepare programmable procedures.
SPANS	Spatial Analysis System from Intera Tydac Inc.
SPOT	Systeme Probatoire d'Observation de la Terre, the French satellite with panchromatic and multi spectral scanning capabilities
SRF	Sundarbans Reserved Forest
TFAP	Tropical Forest Action Plan
TM	Transverse Mercator
TM	Thematic Mapper
TOR	Terms of Reference
TSP	Temporary Sample Plot
UNDP	United Nations Development Programme
UTM	Universal Transverse Mercator projection
UV	Ultraviolet
WC	Working Circle

PLANT SPECIES LIST

The following lists plant species that have been used in this report and also includes some used in outputs prepared as part of this series of consultancies.

Amur	***Amoora cucullata***
Baen	***Avicennia officinalis***
Dhundal	***Xylocarpus granatum***
Gewa/Gengwa	***Excoecaria agallocha***
Golpatta	***Nypa fruticans***
Goran	***Ceriops decandra***
Hantal	***Phoenix paludosa***
Kankra	***Bruguiera gymnorrhiza***
Keora	***Sonneratia apetala***
Jir	***Ficus retusa***
Passur	***Xylocarpus mekongensis***
Singra	***Cynometra ramiflora***
Sundri	***Heritiera fomes***

INTRODUCTION

This reports on the fourth and final brief mission to BGD/84/056 in Khulna, Bangladesh, from 5 April 1995 (arrive Bangladesh 5 April, Khulna 7 April) to 29 April (departing Khulna 20 April, Bangladesh 21 April). It summarises the four missions and is the final report by the Mangrove Inventory Consultant. It supersedes the three earlier interim mission reports.

The Terms of Reference for the first mission are attached as Appendix 1. The original intention was to split a one month Unspecified Consultancy into two separate missions so that during the first mission progress could be reviewed and suggestions made, and then in the second mission, the outstanding problems could be resolved, statistical model development could proceed, and the implementation of the growth and yield prediction system continued. All this has had to be carried out with great haste because of the past delays in the project and the need to meet the extremely tight deadlines that have now been imposed. During the second short mission it was evident that further short missions would be required and two more missions were carried out, a total of four short missions of approximately 2 weeks each on site in Khulna.

This final report unashamedly builds upon earlier interim reports.

The various interim reports detailed immediate, feasible objectives that were absolutely essential for project success and that, when completed, would provide the essential information for incorporation into the IRMP (Integrated Resource Management Plan). All these objectives fit within a framework that is considered essential if the Forest Department is to effectively manage this fragile and complex ecosystem in a sustainable manner.

OBJECTIVES

The TOR provided the basis for undertaking the mission, but does not clearly focus on the real objective of the mission. The TOR were not updated between missions.

Management of the Sundarbans

The Sundarbans is an extremely complex and fragile ecosystem that has a high public and political profile in the Bangladesh psyche. It is essential that it be managed wisely for the benefit of the country, both now and in the future.

Timber production is only one of the major utilisation aspects of these forests, and must not be considered in isolation. The primary objective of the Project is the preparation of an Integrated Resource Management Plan (IRMP), a plan that will assist the Forest Department to manage the ecosystem to best effect. The sub-objectives relevant to this Consultants TOR could be restated as:

- to provide estimates of change in the timber resource now, by species and by size class,
- to provide predictions of current growth rates so that the level of cut can be better assessed,
- to integrate this into an integrated planning framework, and,
- to provide the basis for an ongoing monitoring system.

All this will assist in starting to provide the information necessary for the review and determination of the sustainable production of wood resources for the various user groups.

The Mangrove ecosystem is fragile, subject to rapid ecological change, and it may be difficult to control or to reverse these changes. A simple indicator of this is that a 1 m increase in mean sea level might completely destroy the Sundarbans. What is needed by the Forest Department is a system to manage the changes that will undoubtedly continue to occur.

Over the years there have been three major planning efforts, Curtis (1933), Forestal (1960) and in 1983 by ODA (Chaffey et al 1985), but the apparent differences between the 1960 and 1983 estimates has led to considerable debate about stratifications and estimation procedures and methods. The reports indicated that earlier estimates may have been incorrect, but which estimate, if either, was correct? The data base was relatively poor and no work had been carried out for the last decade. The real need was for better, timely information so that better management planning decisions can be made.

One indicator that the ecological changes are occurring is the prevalence of what is described as top-dying of Sundri. A lot of research effort has gone into attempts to resolve this problem and there are many theories, but seemingly little hard observational data. Now, the main issue to management should be how to manage the change, not on what is the cause, nor even on how to solve the problem, although these are obviously important.

In his 1994 report Larsen recommends that the current constraints on harvesting Sundri top-dying trees be changed and that salvage be accelerated. Although this seems contrary to the general principles of sustained yield and annual allowable cut (AAC) levels, and the felling moratorium, it seems to be the both sensible and appropriate. General discussions suggest that the top-dying areas should be managed on a continuing salvage basis and that only the non top-dying affected areas should be managed on an AAC approach. The difficulty is to demarcate the boundaries between these two Working Circles in the complex mosaic of the Sundarbans, boundaries that are both difficult to define and dynamic. Compartment or sub-compartment boundaries seem to be far too coarse a resolution for practical forest management.

During a field inspection during the second mission it was obvious that in at least one case a Sundri tree had been marked for salvage felling although the crown was extremely healthy and there was no obvious reason for removal apart from a broken top from some past damage, possibly cyclonic. Dr A.Karim has provided the exact location of this tree. It is essential that only extremely unhealthy trees should be removed in salvage felling. Salvage felling should not be used as an excuse to exceed what could be considered the appropriate AAC level.

This dynamic ecological evolution of a complex and fragile ecosystem, and the need to be able to effectively manage change, is at the heart of the suggested approach for a future monitoring system. This can only be fully implemented after this project is complete, but the work proposed in this report will meet the short term objectives while fitting in with this longer term framework.

Specific Objectives

In his mission report Pushparajah (1994) noted some of the information necessary for the preparation of the Integrated Resource Management Plan. The information that he considered essential for the IRMP that is relevant to this particular consultancy included the following components.

- Yield regulation, including how the yield is to be regulated.
- Working Circles, eg Sundri WC, Gewa WC, areas and volumes.
- The Silvicultural management system to be adopted.
- The estimation of annual increment and yield for each Working Circle.
- The determination of the Annual Allowable Cut and how this is distributed by compartments.
- The research necessary to improve these estimates.
- A reforestation programme.

Pushparajah considered that data by forest type (area, stand and stock tables, increment) are required.

It was never the intention of the project document for this project to carry out a forest inventory of the SRF that would update the previous Forestal and ODA inventories. That was to be carried out as a separate project. The Chief Conservator of Forests at a meeting on 5 March 1994 confirmed that the field work under the FRMP would be carried out in the Sundarbans in the 1996/97 dry season and that the report would be available at the end of 1997.

Thus in early 1994 it was evident that the information considered essential for the IRMP by Pushparajah, and also by other project staff, would not be made available and that the Project would have to either use past information alone or supplement past information with new data. Given that the only available data were at least 5 years out of date, and that the ODA survey was some 10 years previous, some limited measurement or remeasurement was necessary.

Almost immediately in March 1994 the project, Dr A.Karim the Mangrove Silviculturalist, planned to commence remeasurement of the series of 120 PSP's (Permanent Sample Plots). These had been established on the sites of some of the ODA plots in 1986/87. These plots had been measured in 1986/87 and some of the plots had been remeasured in 1987/88 and 1988/89. It was planned to use the remeasurements as the information base for the provision of information for the IRMP. The PSP's are extremely limited in scope. They are well demarcated and obvious, are quite correctly protected from felling operations, but this means that they will over time become increasingly unrepresentative of the forest. They are few in number. They cannot be used as an unbiased inventory of the current forest, but they can provide very useful information. Remeasurement of these data was all that could reasonably be attempted in the limited time available.

This series of brief consultancy missions was established to assist project staff provide the information considered essential for the IRMP, recognising that the precision of the estimates would not be completely satisfactory but would be better than anything else that was available. This in turn led to the decision to define a longer term strategy for the provision of necessary information that is at the heart of this report, while at the same time using the available data in the most efficient manner to provide the essential short term project objectives.

During the first 2 week mission a framework for action was proposed and the immediate concerns addressed. The second mission enabled the various problems that arose in the interim to be addressed and a more detailed work plan prepared. The third mission further addressed various problems and continued the development of the procedures to provide the necessary information for the IRMP. The fourth mission was planned to coincide with the fielding of the Forest Management Consultant, but Mr M.Pushparajah was unavailable, and Mr A.Mitchell agreed to undertake his TOR as well as his own. The fourth mission was largely spent assisting with the preparation of outputs and text for the IRMP.

REVIEW OF PROCESSING OF THE PSP DATA

The primary item in the TOR for the first mission was to assist the project team in reviewing and analysing progress made with processing of the PSP (Permanent Sample Plot) data from the Sundarbans. Over the four missions this evolved into ensuring that the best use could be made of the PSP's that have been able to be, or are planned to be, remeasured.

There are some 120 PSP's in the Sundarbans that were selected from the plots established for the ODA survey. In 1986/87 some 105 plots were selected from the ODA plots and these were then remeasured although the ODA field measurements were not available. When it was found that these are almost all in the mixed Sundri-Gewa forest, a further 5 were re-established in the Keora and 10 in the Goran.

By December 1 1994 some 53 of these had been remeasured in the Sundri and Gewa forest areas. Arrangements were made to facilitate further PSP remeasurement in order to reduce the chance of biassing the resource estimates. However by early February 1995 only a further 7 PSP's had been remeasured in the Goran areas at the western part of the SRF, and by April a further 9 across the SRF. It is still highly desirable if all PSP's can be remeasured even though the results may not be able to be completely incorporated in the IRMP. This should include those PSP's that are in current or planned Wildlife Sanctuaries as these will provide good control information in the future.

These plots are 0.2 ha in area (100 x 20 m), and the species, diameter and tree category of all trees has been recorded at each remeasurement. Trees can generally be located at subsequent remeasurements. At the 1994/95 measurement the height of each tree has been recorded, but sample tree heights, or no tree heights, were obtained at some earlier measurements. For the earlier measurements tree height samples were apparently selected haphazardly or at random.

Plots are not hidden and are quite visible. Plots are located by paint and a blaze on a tree on the bank, and a series of paint marks leads into the plot. Plots location is recorded on a map.

Work continued during the missions on defining the codes to be adopted, on defining the data base structure for the IDB, on modelling the necessary components, and on determining the appropriate systems structure for the preparation of volume estimates. The standard procedures for plot measurement will also need to be completed and added into the IDB (the Integrated Data Base).

Integrated Data Base Structure

The Computer Programmer, Mr B.C.Sarker, has implemented a large, complex, and very useful, integrated data base (IDB) structure so that all the elements of this diverse project can more effectively be integrated. The PSP data base is just one section of that data base. Within the PSP part of the main data base there are two streams, textural and the formal mensurational data base.

At various stages advice was given concerning the structure of various data base structures, procedures and components, and changes have been made.

This data base structure will continue to evolve over time and implementation should continue to be given a high priority. It will be an extremely useful and important forest management tool, but it will need to be continually maintained and supported after the completion of the project. It should not be viewed as being of use just to the Project. It should be the starting point for the operation of the Operational Unit (OPSUNIT) which should be under Forest Department jurisdiction and should be based at Khulna. This unit would provide the sound technical base for the planning of the Sundarbans and coastal areas.

Plot measurement, data entry, and validation of the PSP Data Base

Simple inspection of the field sheets for some of the 53 PSP's that had been remeasured as at December 1994 showed a considerable number of possible errors in the data. Proper correction of these errors will necessitate revisiting some of the plots in the field.

It was very pleasing to note that Ms Shubhra Farzana, under the direction of Mr B.C.Sarker, has been able to keep the data entry almost completely up to date after the initial major effort in late 1994. The extra plots will be entered as they become available.

The data base validation checks necessary were defined in some detail during the first mission, and these have been implemented by Mr B.C.Sarker. During the second mission advice was given about tightening up the validation checks. Mangrove forest is not easy to measure and is very slow growing, which makes forest mensuration quite difficult. However the project has no option but to use the best data available, and that is the information from the available PSP's.

The PSP measurement programme should have been commenced at least a year earlier for then it would have been possible to prepare a comprehensive field measurement manual and to train measurement crews to a competent level before field work was commenced. The working environment is difficult. Dr A.Karim arranged to get the plot measurement to the stage where about 50% of the plots have been remeasured. It is now hoped that the Forest Department will be able to complete the task. It is a pity that all 120 plots have not been remeasured.

However, data collection accuracy was uncertain. A limited remeasurement by Mr A.Mitchell of random sections of 4 PSP's indicated that although measurement problems existed, overall the measurements were unbiased.

It is highly desirable to remeasure the plots that have not been remeasured by the Project as this will provide a data base less subject to questions of possible selection bias. This should include those PSP's that are in either current or planned Wildlife Sanctuary areas as the information might well provide the start of a long base line of useful information.

Limitations of the PSP's

There are a number of limitations to the value of the remeasurements of the PSP system.

The most important difficulty has been caused by the imposition of a decree which has banned official harvesting from the PSP's. This decree was logically correct and should continue to be enforced, but it causes some difficulties for the analyses necessary for the IRMP because the PSP series is the only plot series available as representative of the SRF.

The PSP's can be regarded as an unbiased sample of the SRF in 1986/87 but this is no longer tenable in 1994/95. What is needed is a series of plots in areas where there have been official harvesting operations, what is needed is a proper forest inventory. There is no really suitable data base that can be used to determine the net change in status of the SRF. For the IRMP it is essential to use the PSP series to make inferences since these will be better than any alternative, but the inferences must necessarily be inexact.

Also, used on their own, there are obviously insufficient samples.

A later section provides more detail of a proposal to measure a mixture of Permanent Sample Plots (PSP's) and Temporary Sample Plots (TSP's) with the current 120 PSP's being augmented by a relatively few extra plots, but a new TSP system including approximately 1300-1900 plots on a 1 minute systematic grid depending on whether water is included as a separate TSP.

The approach suggested clearly demarcates two types of plots. The PSP's provide precise detailed remeasurements of the site and which can include research trials where different silvicultural practices may be tried and evaluated. The information should cover a far wider range of silvicultural and management conditions than is likely to occur in practice. They are therefore not necessarily typical of the current forest estate. On the other hand the current forest condition would be monitored by the large TSP system where less detailed information will be collected over a larger number of plots. The PSP's can be sited to achieve homogeneity, the TSP's must be measured on the exact location and will be heterogeneous.

The advent of the Geographic Information System (GIS) with its ability to quickly define alternative stratifications of the forest estate predicates that the plot measurement and stratification should be independent of one another. The arguments about the differences between the Forestal survey and the ODA survey seem to resolve into challenging the respective stratifications. Gaining this independence between plot measurement and stratification comes at the cost of losing any statistical advantages to be gained from the use of stratified random sampling, but the longer term flexibility appears to make this the most appropriate methodology.

The limitation with the current situation is that the PSP's had, in essence, to be used as both PSP's and TSP's, being used to develop the models and to assess the current status of the forest. The difficulty is that there are barely sufficient plots for simple model development, and far too few plots to give anything other than an indicative assessment of the current status of the Sundarbans.

Other necessary information

The PSP's provide estimates of growth, ingrowth and consumption. However a decree by the Forest Department that no felling should be carried out in any PSP means that any consumption is unofficial (including mortality) rather than official. Therefore it is necessary to obtain official felling records, by species, and preferably by relatively small area units, such as at compartment level or at range level, so that the actual net change in status of the SRF can be better assessed. The Natural Resources Economist, Mr A.Mitchell, and previous National Project Director, Mr N.Howlader, have obtained the historical information for the whole of the SRF.

IMPLEMENTATION METHODOLOGY

During the earlier missions an implementation methodology was prepared that had the primary objective of providing the essential forest resource information for the Integrated Resource Management Plan (IRMP). The PSP remeasurement activity had been implemented only late in the project, and the plots have considerable limitations, and so it is not possible to provide anything other than indicative statements about the forest resource in the SRF. However the methodology suggested does fit in to the philosophy for the future that is proposed in more detail later.

It must be continually remembered this project has never had an inventory component. Thus the project is severely hampered by the lack of suitable data and this led to the recognition that it was necessary to, at the very least, remeasure the PSP's. The IRMP was definitely not intended to provide estimates of the AAC, or cutting plans, or cutting schedules, but is able to provide some updated indications, at a very broad level, of the current status of the SRF.

The project really needed estimates of the current status of the forest including growth, ingrowth and consumption. The only practical approach was to take the 1986/87 and 1994/95 measurements on as many PSP's as could possibly be remeasured, hopefully close to the total of the original 120 may be available before the project terminates, and including those plots now located in current and proposed Wildlife Sanctuary areas where it is planned that felling operations will not be carried out.

The methodology proposed is not very sophisticated nor will it provide very precise predictions, and the analysis that will be possible, based on the information provided, will be very limited. However the approach adopted was to determine the best estimate that could be achieved in the available time, an approach that is in balance with the quality and quantity of the available data, and will at least provide some basis for planning in the future.

One factor which was critical to the formulation of this methodology was the nature of the PSP's themselves. They were originally established by the ODA survey and then these 120 plots were remeasured in 1986/87. At that stage (1986/87) the 120 PSP's do provide an unbiased estimate of forest status, in essence a very poor inventory (actually currently only 69/120 plots compared with the 2099-4000 plots for the ODA inventory and approximately 4000 plots of the Forestal inventory. But at least the PSP's have been measured in 1994/95.

However for all the right reasons a moratorium was placed on felling in the PSP's. They were to be kept for growth purposes. This means that for this particular project the PSP's are now a biased estimate of the forest since they should not have had any consumption at all. The plots can provide estimates of:

- growth, based on trees present in 1986/87 and 1994/95,
- ingrowth, based on trees not present in 1986/87 but present in 1994/95,
- unofficial consumption (the loss from the forest and including mortality) based on trees present in 1986/87 but not present in 1994/95.

Official consumption is not available from the PSP's but is only available from the official felling records of the Forest Department. The available records were unfortunately available only at an aggregate level across the whole of the Sundarbans for the late 1980's, although information from later years can be obtained at the compartment level.

This means that it is not possible at present to determine net growth between the 1986/87 and 1994/95 measurements at any level less than the forest estate, which is rather a pity.

For each PSP stocking, basal area, and, volume can be calculated. Volume estimates are based on tree volume equations, either those developed by the ODA or those developed during this Consultant's missions. This information is by species, and can be summarised as:

- stocking,
  - standing at 1986/87,
  - standing at 1994/95,
  - trees present on both occasions (growing stock),
  - trees present only in 1986/87 (unofficial consumption including mortality),
  - trees present only in 1994/95 (ingrowth),
- basal area,
  - basal area of trees standing at 1986/87,
  - basal area of trees standing at 1994/95,
  - trees present on both occasions (growing stock),
    - basal area at 1986/87,
    - basal area at 1994/95
  - basal area of trees present only in 1986/87 (unofficial consumption including mortality),
  - basal area of trees present only in 1994/95 (ingrowth),
- volume,
  - volume of trees standing at 1986/87,
  - volume of trees standing at 1994/95,
  - trees present on both occasions (growing stock),
    - volume at 1986/87,
    - volume at 1994/95
  - volume of trees present only in 1986/87 (unofficial consumption including mortality),
  - volume of trees present only in 1994/95 (ingrowth),

and this information can be obtained by diameter class if desired.

These PSP estimates can then be aggregated to produce averages of each of these statistics, by species, across the PSP's that fall within any particular stratum of the forest. The SRF has to taken as one stratum for the IRMP as the official consumption has to be considered before any net change in status can be determined.

The methodology used allows net change in the SRF to be estimated for any stratification (but unfortunately this must be extremely limited in scope for the IRMP) as:

Part Growth = growth on the growing stock component (1994/95 - 1986/87)
+ ingrowth
- unofficial consumption (which includes mortality)

This estimate based on the PSP's is then aggregated by a stratification that matches the level of disaggregation possible for the official consumption, and then

Net growth = Part growth
- official consumption

and this net growth estimate provides an indication of the changing status of the SRF.

It is worth noting that Forestal and ODA had many more plots, but they had extremely limited growth information. This analysis of the PSP data provides a better estimate of growth and ingrowth, and an estimate of unofficial consumption (which in this sense includes mortality, missing trees and also any illegally felled trees). It does not provide a good estimate of the growing stock in the forest.

This methodology is the first step towards a consistent, coherent methodology that is described later in this report.

The PSP data base does provide a good basis for the development of some indicative forest mensurational models. If all the following models could have been developed then they could have been incorporated into the calculation procedures, thus improving prediction precision somewhat for some components, although they would not have improved the overall analysis of change in status of the SRF.

TREE HEIGHT ESTIMATION

Tree heights were recorded for all trees only at the 1994/95 measurement. At some earlier remeasurements, on some PSP's, sample tree heights were measured, at others no tree heights were measured at all.

What was desired was a way of estimating all tree heights at the earlier measurements based upon the sample trees. However the relatively few trees at earlier measurements makes estimation under such circumstances difficult.

Methodology

The method for predicting tree height from diameter that was considered most appropriate can be summarised as follows.

- Extract the 1994/95 PSP data, species, diameter (D) and tree height (H).
- For each species separately plot (H) on the Y axis against (D) on the X axis.
- This generally should show that as diameter increases height approaches an asymptotic maximum value.
- Develop equations to predict tree height from tree diameter.
    - Simple polynomial models of the form

      $$H = b0 + b1\ D + b2\ D^2 + b3\ D^3 + \ldots$$

      adding terms only as long as the highest order polynomial is significant.
    - Then develop the Johnson-Schumacher form exponential equation, initially by fitting the logarithmic transformation model

      $$\log(H) = b0 + b1\ /\ D$$

and calculating the retransformed error sum of squares and bias when (H) rather than (log(H)) is used. In all this report natural logarithms should be used not logarithms to the base 10.

The parameter estimates from this linear transformed model can be used as the starting values for estimating the nonlinear form:

$$H = \exp(b0 + b1 / D)$$

which has the advantage of avoiding the logarithmic bias, and also providing error sum squares that enable direct comparison with the simpler linear untransformed model structures.

If for some reason it is impossible to calculate the nonlinear models then the linear logarithmic transform model could be used but it must be corrected using a procedure such as detailed by Meyer (1944).

- The value of (exp(b0)) should be very approximately equal to the tallest feasible tree height, but given that the SRF has been logged for years it may be less than the likely maximum height.
- Now, for the first measurement in 1986/87, but also if possible the other measurements, use this model to predict the heights of any sample trees that have been measured.
- Calculate the mean error and the standard deviation of the errors based on this estimate.
- A t-test can be used to determine whether or not the mean is significantly different from zero. Estimated (t) is calculated by dividing the mean error by the standard deviation. If this is greater than the critical value of (t) from t-tables (using number of samples minus 1 as the number of degrees of freedom, and the 5% probability table), then the model is significantly in error.
- If the sample tree height estimate for any particular year is not significantly different then the 1994/95 based model can be used to estimate the heights of all trees in the plot and the figures entered into the data base as estimated tree heights.
- If the mean error for all or some sample measurements are significantly in error then the mean error may show a trend.
    - Calculate the ratio for each measurement of (mean sample height minus mean error) divided by mean sample height.
    - If these show a reasonable trend then use them, but if they are quite different, smooth out the estimates by plotting the average correction factor against measurement period.
    - Use the corrected model to estimate the height for each tree at each measurement by multiplying the estimated tree height using the 1994/95 equation based on actual diameter by the ratio in the previous one or two steps for the relevant measurement year.

- These estimated tree heights can then be entered into the Integrated Data Base in a separate field.

There is no certainty that this approach will always be statistically satisfactory, but it will provide a methodology that can provide tree height estimates for all trees regardless of whether they were all measured or not.

Analysis

This methodology was used by the Statistician, Ms Nazma Ahmed, to prepare the necessary prediction equations for each the 60 PSP's available at February 1995. These analyses were completed and a draft report was prepared. Correction factors were calculated for the few plots where there had been heights measured at the earlier measurements. None of these correction factors was significantly different from zero. This was not really surprising as the sample size was small and precise tree height measurement is difficult.

Therefore it is not unacceptable to use the models based on the 1994/95 measurements to predict tree heights at earlier measurement times. However the improvement in the precision of tree volume by using tree diameter and estimated tree height compared with diameter alone was impossible to quantify in the limited time available after the Statistician separated from the project.

Having considered the analyses carried out, the tree volume equations, and the PSP data in general, any gain is believed to be minimal.

TREE VOLUME EQUATIONS

Tree volume equations are required so that the diameter measurements recorded on the PSP's can be used to predict tree, and hence stand, volume for each species.

ODA Equations

A review was made during the second mission of the tree volume equations that are presented in the ODA report (Chaffey, Miller and Sandom 1985) as these seemed to be a distillation of all available equations for trees in the SRF.

The reported equations are all linear logarithmic transform model structures with generally 2 variables (log(D) and (D)) and the equations are presented in Table 32 of the report. The text reveals, page 107, that the equations reported in Table 32 were developed only for Sundri, Gewa and Keora, and that the other equations are from Forestal (1960), which in turn seem to have come from Curtis (1933) or possibly from Suri (1928). It would appear that the Curtis tables, which would have been graphically smoothed averages, were used as the data in the regression analysis to provide the ODA equations for these species.

The use of the logarithmic transform causes biased estimates and no evidence was found that this bias had been removed although it is quite feasible statistically (Meyer 1944). Experience suggests that weighted linear regression or nonlinear parameter estimation techniques are statistically superior to the use of logarithmic transforms to stabilise the error variance.

For Baen and Jir, the equations are apparently based on Curtis (1933) graphically smoothed average yields, and standard errors of the parameter estimates are obviously not presented as they are gross underestimates. It was thus not statistically possible to determine whether the 3 height class equations are significantly different from one another, or whether a combined equation would be more appropriate. Experience and the values of the parameters themselves suggest that one model may well have been a better statistical option.

For Passur and Dhundal the equation for height class 3 does not make sense in that there are two constant terms and two linear terms inside the logarithm brackets. This seems to be mistyped, but it was not possible to determine what the correct model should be.

Even the equations that ODA seem to have developed themselves do not have parameter standard errors presented, and no indication could be found of the statistical procedures carried out. Sufficient information to be able to properly assess the models was not found.

Analysis showed that one Sundri equation seems to be mistyped in the ODA report for it provided volume estimates close to zero. The other two equations showed that for commercially viable tree diameters the models for Sundri underestimated tree volume because of the nature of the equations used. It is suggested that the ODA equations should not be used for Sundri.

However the ODA report does provide a set of tree volume equations that could possibly be used to process the data. They provide an alternative against which any other equations can be compared.

It was decided that the Project needed to collect some tree volume data from felled trees and so enable a better analysis to be made.

Methodology

Dr A.Karim established 6 plot sites, out of an originally proposed 15-20, and arranged for the felling and measurement of sample trees. It had been hoped that he would be able to find time to measure more sites and species. However these limited data could still be used to develop an alternative set of equations to those of the ODA. The felled tree measurement methodology used broadly followed the suggestions of the first mission report, and will hopefully be detailed, including measurement procedures, in the final report by Dr A.Karim.

A number of possible equation forms can be evaluated, including

$$V = b0 + b1 * D$$

$$V = b0 + b1 * D + b2 * D^2$$

and various other higher order polynomials. The power function should also be evaluated

$$V = b1 * (D ** b2)$$

as experience suggests that this may well behave better for smaller tree diameters.

Equations can also developed using height and these are expected to be far better predictors of tree volume. Models should include

$$V = b0 + b1 * D^2H$$

$$V = b0 + b1 * D^2H + b2 * D^2$$

$$V = b0 + b1 * D^2H + b2 * H$$

$$V = b0 + b1 * D^2H + b2 * D^2 + b3 * H$$

and also the power function

$$V = b0 + b1 * (D ** b2) * (H ** b3)$$

which is likely to be the best model form.

But what should be used for species other than Sundri and Gewa? Analysis of the first 53 plots measured showed that these PSP's were in what could be described as the Sundri Working Circle and that none had been measured in the Goran Working Circle towards the western side of the Sundarbans. Of the trees where species was recorded 96% were of either Sundri or Gewa, and so using the ODA equations for the other species would not cause great difficulties. It must be emphasised that this assumption only holds for these first 53 plots and that it obviously does not hold for the 7 PSP's remeasured in the Goran areas.

The equations must be developed using WLS (Weighted Least Squares) rather than OLS (Ordinary Least Squares) as the variance of the dependent variable will undoubtedly be heteroscedastic.

Equations to predict under bark volume, and also to predict volume to arbitrary top diameter limits, are also very desirable. However it is necessary to adopt a model structure that ensures that the predictions are compatible between the different dependent variables and that, for example, predicted volume to 10 cm top diameter is always greater than, or at least the same as, volume to 20 cm top diameter. It is not always easy to ensure that this holds over all the range of diameters using the model structures above. The most logical approach is to develop a model to predict total stem or bole volume and then to develop secondary equations to predict the proportion of that total stem volume that is to any arbitrary top diameter limit. This method can be used to ensure the necessary compatibility.

However given the poor quality of the felled tree measurements available, and the limited number of samples, care must also be taken not to use too complicated a methodology.

Analysis

There were approximately 160 Sundri and 60 Gewa trees collected across the 6 sites. The Sundri data were partially analysed during the second mission and the results were reported in Appendix 3. The data were corrected as far as was practicable in the available time by Dr A.Karim and Mr B.C.Sarker. The data were revalidated. The equations were rerun during the third mission, the analysis extended, and the Appendix was corrected and updated.

Before the third mission the Mrs Nazma Ahmed had taken the data base and had recalculated the tree volume equations for Sundri and had calculated some equations for Gewa. These were reviewed during the mission. The models were in general unsatisfactory.

Appendices 3 and 4 detail Sundri and Gewa equation development. These include equations using tree height, but merchantable height or other height measurements could just as easily be used.

Based on Appendix 3, as revised during the third mission, the most appropriate equations to predict merchantable tree volume over bark for Sundri are as follows. Trees less than 10.0 cm dbhob should be assigned zero volume.

```
V =  0.00017809  * (D ** 2.3358)

V =  0.000006083 * (D ** 1.9631) * (H ** 0.8270)
```

For Gewa two alternative equations were required that would predict merchantable volumes to both a 5 and a 10 cm top diameter limit (V05 and V10). The analysis was also carried out during the third mission and the results are reported in Appendix 4. It was necessary to develop a model to predict over bark volume between stump and the tip of the tree and then develop models to predict the volume between the tip and 5 cm and 10 cm top diameter. It was also necessary to ensure that the models are consistent over the complete likely range of tree diameters.

These models are as follows.

```
V05 = 0.0004218 * (D ** 2) - 0.001502 - 0.008738 / D        if D>= 5.0
V05 = 0.0                                                       D<  5.0

V10 = 0.0004218 * (D ** 2) - 0.002032 - 0.2506   / D        if D>=10.0
V10 = 0.0                                                       D< 10.0
```

These equations can be coded and used in the prediction procedures of the IDB to prepare outputs for the IRMP.

If it is desirable to estimate volume to some other top diameter merchantable limit less than 10.0 cm then one simple approximation would be to assume that the difference between the 5 and 10 cm top diameter limit can be approximated by a frustrum of a cone. For the 7 cm top diameter limit currently used by KNM (V07) this results in the following equation.

```
V07 = 0.75 * (V05 - V10) + V10                                 if D>= 7.0
```

This is obviously biased for trees between 7.0 and 10.0 cm dbhob but could still provide useful estimates for KNM.

The use of dbhob (D) as the critical point for volume to the same top diameter merchantable limit is also likely to introduce a slight bias, but experience suggests that any bias is minimal and, considering all the other mensurational problems that occur with these analyses, is considered acceptable.

Summary

Equations have been developed for over bark merchantable volume for Sundri that are better than using the ODA equations. Under bark equations should be developed but time was not available during these brief missions. The under bark measurements have more errors than the over bark measurements, which makes verification, validation and analysis more difficult.

For Gewa, over bark equations have been developed to predict volume to both 5 and 10 cm top diameter limits, the alternative merchantability limits used in the field work, and a method for estimating volume to 7 cm top diameter limit is suggested. These should also be redeveloped as under bark equations when opportunity permits.

It is recognised that by using these equations they are inconsistent with the ODA equations which are under bark equations. However given the problems that are known to occur with the ODA equations for Sundri it is inappropriate to use them just to enable under bark predictions to be made.

Some 96% of the basal area in the first 53 PSP's measured (primarily on the eastern part of the SRF) is in Sundri and Gewa, and so the other species will have a very limited, but still important, effect in the overall review of the status of the forest resource in the SRF. The problem with the ODA Sundri equations occurs, in principle, with some other species, but the magnitude of the effect is far less as it occurs only for a few very large diameter trees and not for all trees over 24 and 28 cm dbhob as it does for Sundri.

The most appropriate equations seem to be as follows.

- For Sundri use the estimated over bark volume from stump to merchantable height, the merchantable volume,
- For Gewa use the estimated over bark volume from stump to the arbitrary 5 cm top diameter limit, although the equations to predict volume to 10 cm top diameter limit are also available,
- For all other species, use the under bark equations used by ODA.

DIAMETER INCREMENT PREDICTION EQUATIONS

The original intention had been to develop diameter increment prediction equations and to use these for each plot separately so that the 1986/87 measurements of trees felled during the interim could be projected to 1994/95. It seemed that this would have enabled an estimate to be made of the expected 1994/95 measurements as though there had been no felling at all. This makes a theoretically untenable assumption that the site would have been able to support the growth of the extra trees. When it was realised that there was no official felling in any PSP's it did not seem sensible to continue this approach for direct incorporation into the IRMP.

However the development of the equations continued as a lower priority task as they would provide a growth estimate that could be used in the future when a suitable inventory becomes available, perhaps from the TSP system described later in this report. The analysis would also provide the first step in the development of a more generalised tree diameter growth model for the SRF.

The dilemma is that the ODA survey provided an inventory, but apparently had scanty growth information for preparing resource estimates, while this project has better, but still limited, growth data, but no data that could be used as an appropriate inventory of the forest. The problem stems from the initial project design and the later decision by the Forest Department not to measure inventory plots during the term of the project, and to a lesser extent, from the inability to disaggregate official harvesting to the compartment level for all years since 1986/87.

Methodology

Analyses were carried out for each plot in turn. Only trees present at both the 1986/87 and 1994/95 measurements were considered. A nonparametric box plot technique (Tukey 1977, Hettmansperger 1984) was used to screen the data in a FORTRAN program specially written for the task. The code for this program, and the procedures for the analysis, was left with Mr B.C.Sarker.

The annual diameter increment was calculated by dividing each trees diameter increment by the decimal number of years between measurements and graphed against diameter in 1986/87 to see the variability present. The data showed considerable variation and it was obvious that good models could not be obtained.

The following extremely simple equation forms were considered,

$$\text{pai}(D) = (D_{1994/95} - D_{1986/87}) \ / \ \text{interval}$$

where (interval) is the time interval in decimal years between the 1986/87 and 1994/95 measurements,

$$\text{pai}(D) = b0$$

$$\text{pai}(D) = b0 + b1 * D$$

$$\text{pai}(D) = b0 + b1 * D + b2 * D^2$$

$$\text{pai}(D) = b1 * D$$

and

$$\text{pai}(D)/D = b0$$

$$\text{pai}(D)/D = b0 + b1 \ / \ D$$

$$\text{pai}(D)/D = b0 + b1 * D$$

$$\text{pai}(D)/D = b0 + b1 * D + b2 \ / \ D$$

with the latter structures likely to have more homogeneous errors and therefore be statistically superior.

Analysis

During the second mission a detailed analysis was not feasible in the available time but exploratory procedures were written using GLIM and some equations were developed. This analysis was later duplicated by Mrs Nazma Ahmed who developed a procedure in Genstat 5.

It would seem that a simple linear model predicting diameter increment from tree diameter seems to be as good as any on most of the plots tested, and this model could be used for projection purposes if plot by plot projections are desired for reporting in the IRMP. These equations could possibly provide a simple basis for a transition matrix approach to the approximate development of a growth model and the determination of rotation length.

Extension

It had been hoped that there would be time to develop a diameter increment prediction model along the following lines, thus providing an equation that could be used to predict future growth for the SRF and not be restricted to being used only on the PSP's. The PSP analysis was to be the first step towards the development of this model.

A number of tree and stand based variables can be defined as follows.

TBA	Total standing basal area at the first measurement across all species.
SBA	Standing basal area at the first measurement for the species of interest.
RBA	SBA/TBA for the species of interest.
OBA	The basal area of trees with diameter (D) greater than the tree of interest (see Vanclay 1994 for discussion of overtopping basal area).
H	Standing upper stand height at the first measurement.
V	Vegetation type according to the ODA survey.
TR	The ratio of tree diameter (D) to the quadratic mean diameter (the diameter corresponding to mean basal area of the trees in the plot).
SR	As for TR, but the quadratic mean diameter is based on the relevant species and not across all species.
TN	Stocking per hectare of all trees at the first measurement.
SN	Stocking per hectare of all trees at the first measurement of the relevant species.

The dependent variable is likely to be similar to that from the earlier analyses for each PSP, periodic annual increment in tree diameter, or the ratio of pai(D) to tree diameter. The independent variables can be extended by incorporating these stand based variables, either singly or in combination with tree diameter.

It is expected that a relatively simple model structure is all that reasonably can be prepared given the nature of the available data, but alternative more complex and better methodologies are described in some detail in Leech (1993) and Vanclay (1994). Such a model will be useful for making growth predictions for the future based on any PSP or TSP plot information.

INTEGRATION OF THE MODELS INTO THE CALCULATIONS

Procedures to provide the necessary information have been implemented in Clipper by Mr B.C.Sarker and these have been and will continue to be refined over the latter stages of the project as the PSP data are analysed and alternative calculation methods are defined. The procedures, or parts of procedures, have been discussed during the various missions and assistance provided. Data base structures have been discussed in varying levels of detail. There is little doubt that Mr B.C.Sarker has the ability to prepare the necessary estimates once calculation procedures have been defined.

There are a number of separate procedures that calculate different summaries of different sections of the data base. Some of these are briefly described here. For more details it will be necessary to consult Mr B.C.Sarker.

One procedure calculates tree volumes at any measurement in the PSP component of the IDB. Acceptable models have been defined earlier and defined in more detail in Appendices 3 and 4. It must be remembered that the equations developed for this project are over bark and the ODA equations are under bark.

A separate procedure takes a data base of general equation forms and specific parameters and calculates a particular dependent variable.

A practical methodology for this was discussed with Mr B.C.Sarker and was implemented.

Simple prediction equations based on tree diameter alone will at least provide essential information but an alternative approach is possible. The tree height diameter equations developed by Ms Nazma Ahmed could be used to predict tree height for any tree at any age where tree heights are not available in any PSP. This mixture of estimated and actual tree heights will enable the tree volume equations based on the two variables tree diameter and tree height to be used, at least for Sundri and Gewa, and this may improve the expected precision of the predictions. The improvement would be greater if there were fewer tree heights to be estimated and more measured tree heights at earlier ages. The procedures were discussed with Mr B.C.Sarker.

The tree volume equations should be extended to calculate under bark volumes as well as over bark, although it is recognised that this will be difficult as the under bark diameter measurements are known to have more errors than the over bark measurements.

Clipper procedures have been prepared by Mr B.C.Sarker to carry out the analyses. These need to be checked in some detail and reports prepared. During the preparation of the IRMP there will undoubtedly be a need for producing computer outputs in slightly modified formats for inclusion in that document. A procedure for minimising the difficulty of this has been discussed with Mr B.C.Sarker.

Mr A.Mitchell could then use these plot based summaries across all PSP's in spread sheet compatible format to prepare some of the estimates that he needs for his resource management and resource economic analyses.

However the level of analysis feasible for the IRMP was necessarily very limited by the lack of suitable inventory data and the inability to disaggregate the official felling records.

Implementation Stages

During the first two missions the various implementation stages were defined in some detail, albeit rather tenuously. The process was a continual case of review and reassessment culminating in the final mission where the efforts were addressed at using the information that had already been provided rather than planning any further major tasks. It was necessary to cease developmental work on the models in order to leave time to work on the preparation of the IRMP.

Other activities not necessary for the preparation of the IRMP, but which should be continued as they will provide useful information for the future, include the following.

- Complete the remeasurement of all PSP's.
- Determine the official felling history for each compartment or sub-compartment (or if possible the area around each PSP) since 1986/87.

- Prepare tree volume equations for utilisable volume underbark, total stem volume overbark and underbark, for both Sundri and Gewa.
- Development of diameter prediction equations based on all plot information that can be used generally instead of for just one plot.

The necessity to assist in the preparation of the IRMP to the time frame set by FAO HQ from that previously planned, precluded any major efforts being made on any of these issues during the fourth mission.

The philosophy adopted was to establish a methodology that would provide the best available estimates for inclusion in the IRMP. The attempt was a totally integrated approach to analysing the available information with a single, clear objective. It became obvious very quickly that limitations in the information available would limit the need for complex statistical analysis and that the only task that was absolutely necessary was the development of tree volume equations as the ODA equations as reported could not, or should not, be used. Other analyses were possible given the data available, but they would add almost nothing to the final analysis and conclusions about the changes to the state of the Sundarbans Reserved Forest.

Implementation Responsibilities

The integration of the forest wood-based resource information into the IRMP (currently sections 11, 15, 22 and 23) is the responsibility of a number of national and international staff. The following broadly describes the responsibilities of each as it effects this particular consultant's component in this diverse multi-disciplinary project.

Dr A.Karim	• Measurement of the PSP's. • Measurement of felled trees in temporary plots established for that purpose.
Ms Shubhra Farzana	• Data entry of all field data.
Mr B.C.Sarker	• Maintenance of the PSP data base. • Maintenance of the felled tree data base. • Computer validation of the data bases to determine possible errors in field data.
Dr A.Karim	• Manual validation of the data bases to determine possible errors in field data. • Correction of PSP data. • Correction of felled tree measurements. • Responsible for data precision of both PSP and felled tree data bases.
Mr B.C.Sarker	• Programming of the computer processing procedures used for calculations.
Mrs Nazma Ahmed	• Development of tree height diameter prediction equations for each plot. • Development of equations to predict diameter increment for each plot.

Mr B.C.Sarker	.	Calculation of estimated tree heights for past PSP measurements based on tree height diameter equations for each plot.
	.	Incorporation of tree volume equations into the calculation procedures.
	.	Preparation of PSP per hectare summaries of stocking, basal area and volume by species.
	.	Summarising across all PSP's, or across the PSP's that lie within a stratum, the information for each species, stocking, basal area and volume, as defined earlier.
Mr A.Mitchell	.	Integration of the forest resources estimates into the economic analyses for inclusion in the IRMP.
	.	Supervision of the overall implementation of these tasks in the absence of this Consultant.
Mr P.deV.Moss, and, Mr A.Mitchell	.	Interpretation of the analyses.
Mr P.deV.Moss, and, Mr A.Mitchell	.	Integration of the forest resources estimates into the IRMP.
Mr P.deV.Moss	.	Preparation of the IRMP.

The effective integration of all these activities requires good coordination, team work, and control of all activities to ensure that they are all completed on the almost impossible time frame that has been set.

EXTENDED METHODOLOGY

The preceding section details the analyses required for the preparation of the minimal information for inclusion in the IRMP and also details some analyses that could be carried out that would be useful for the future. There are a number of other models that would be desirable and which should be developed as opportunity permits in the future.

True Volume to Utilisable Volume Conversion Models

Conversion equations need to be developed relating the true volume estimate obtained from the total stem volume underbark tree volume equations to whatever utilisation standards and measures that are needed for any particular analyses in the future.

Experience suggests that although these models are generally imprecise predictors, they cannot be ignored if useful estimates of expected yields are to be obtained. It is suspected that the use of direct prediction of utilisable volume may be one serious reason for the actual yields predicted not matching yields obtained. The ODA estimates of Gewa seem to have consistently been less than the volumes extracted by Khulna Newsprint Mills Ltd., (Mr Anwar Hussain pers.comm.). The difference in top diameter limit between ODA and current practice, which also lowers the minimum exploitable tree diameter, is likely to be one of the two major reasons why this has occurred.

By developing tree volume equations that predict stump to bole height volume directly, as suggested earlier for this project, a great deal of flexibility is lost and the aggregated volume calculations will have to used with great care. It will be far better to develop a single new tree volume equation for each species, total stem volume, underbark, from ground level to tree height, and then to develop methods for converting this to whatever measure is desired in the future for any particular analysis.

The Hoppus quarter girth system should be phased out, as it has been almost everywhere else in the world, and it would be highly desirable if one standard utilisation measure is adopted. It may be necessary to develop conversion models for temporary use.

Unofficial and Official Consumption

One problem in the Sundarbans is that there is a level of partly legal, partly illegal, felling that is in addition to the planned harvesting by compartments. This is likely to have an effect on the growing stock levels. The simplest way to handle this seems to be to divide utilisation or consumption from the forest into two categories, official and unofficial.

Official consumption is that planned by the Forest Department Working Plans and for which extraction records are available. Unofficial consumption includes all other reasons for felling trees, whether approved, partially approved, or not approved. Official consumption refers to the planned schedule, unofficial consumption refers to all other sources combined. This is a slightly different definition to the unofficial consumption used for the PSP summaries where unofficial consumption also includes mortality, although this is for reporting convenience as it can be, and has been, segregated out.

It is suspected that the levels of unofficial consumption levels are high, as can also be inferred from Larsen (1994), and it is suspected that this may be the greatest single source of the discrepancies between successive inventories.

One way of estimating the unofficial consumption is to determine an average drain percentage, perhaps by species, by distance from navigable water, by size class, and by ecosystem type.

The PSP's can only provide a biased estimate of the drain percentage and it would be better determined from the proposed TSP system of plots. It is suspected that even then the data will show great variation as some plots may have a great amount of felling, others little. In this case the simple average drain percentage, across all plots and across available measurement periods, may be all that can reasonably be achieved.

This may assist resolving the debate about Forestal and ODA inventories accuracy. It would also provide a model that can be used in predicting future yields.

Growth, Yield and Other Models

There was almost no time to spend on discussing the possible approaches to growth and yield modelling in the Sundarbans. A copy of a set of Lecture Notes on Growth and Yield Modelling prepared for Project CPR/91/151 in The Peoples Republic of China (Leech 1993) has been left with the Project. This may provide a useful reference as too would Vanclay (1994).

Andel (1993) suggests the use of a very simple tree diameter increment model partly, it is suspected, because this enables some erroneous data to be deleted from the analysis. The approach would provide models which are likely to be biased, depending on how the data are validated. but it may still be the most sensible approach for very short term projections based on current silviculture.

Plots would have to be grouped; either as Andel suggests into changed and not changed, or into site classes, and individual tree data information extracted. Simple linear regression models could then provide estimates of annual diameter increment based on current diameter.

However, unlike the recommendation of Andel (1993), data should not be ignored if negative increments occur in the data base. The problem is one of measurement precision and it is not possible to eliminate all erroneous overestimation of tree diameter increment, so the erroneous underestimates should not be deleted either.

The technique is simple but the data will be relatively poor in the Mangrove forest and so good models will be difficult to obtain. In such situations simple models are to be preferred. The approach that is proposed earlier provides a way around this difficulty but it is limited in its usefulness. The extension to a more general form including stand variables is described earlier. Other alternative techniques are described in Leech (1993) and Vanclay (1994).

For longer term planning it is logically more sensible to predict stand variables such as basal area, upper stand height and volume, rather than tree variables. Tree variables are generally satisfactory only for short term predictions. It is generally better to apportion basal area and volume using stand tables or to use some other, very simple approach.

One of the more complicated techniques, that I have assisted Mr Ge Hongli develop in China that may be of use, is to transform an equation that predicts stand volume from age so that it does not need age but needs increment period and volume at the first measurement instead. Work there suggests that the approach may be quite feasible in any forest of unknown age, but considerable analysis must be carried out to determine this.

The Johnson-Schumacher volume model predicts yield (Y) from age (A) using the following equation.

$$\log(Y) = b0 + b1 / A$$

The use of the logarithmic transform introduces bias into the estimation procedure and it is better to fit such a model in the nonlinear form such as follows.

$$Y = \exp(b0 + b1/A)$$

This is equivalent to the following form.

$$Y = b0 \exp(b1/A)$$

From this it is possible to eliminate age from the equation and instead use the following variables;

Y1 Yield at age A1
Y2 Yield at age A2

and these data will be available from the PSP data base. Then the equation can be transformed to the following.

Y2 = b0 exp(b1 / {[A2-A1] + b1/[ln(Y1)-ln(b0)]})

The model is nonlinear in structure and care must be taken to use an iterative procedure such as the Gauss-Newton gradient method to estimate the parameters, the criterion for stopping the iterations probably being Marquardt's criteria. Computer procedures are available, and Genstat can be used for this provided that good initial starting values of the parameters can be obtained.

Growth model estimation is both difficult and time consuming.

The PSP measurements record recruitment into the smaller diameter classes that has occurred in between measurements and it will be possible to develop a recruitment model in the future. Examples of the model structures that could be tried are included in Leech (1993) and Vanclay (1994). It is expected that a very simple model will be all that can reasonably be developed.

Forest Site and Compartment Classification

The PSP data base has a variable recorded called FT_MAP or the forest type as mapped by the ODA survey. For each plot it is possible to calculate a similar variable, called FT_PLOT, but this is a point sample and there is a spatial resolution difficulty.

The comparison of FT_PLOT with FT_MAP would facilitate comparison of the stratification and should be done as a matter of course and with some urgency when the ODA vegetation and forest type maps are digitised and accessible by Arc/Info. But the spatial resolution issue must be remembered.

Some people seem to hold the opinion that the ODA stratification will be satisfactory, while others seem to disagree. What is needed however is a number of alternative stratifications that can be tried. Given that there are only a maximum of 120 PSP's it is unlikely that a detailed stratification will be of any use at all during this project. It is hoped that this will change in the future.

Provisional Stand Tables

Stand Tables are of use in assisting forest managers understand the status of the forest but they have considerable limitations in that they reflect particular circumstances and conditions and cannot be used for intensive management.

Given the Sundri top-dying problem, the complex mosaic within the Sundarbans ecosystem, the range of species and history of past utilisation, any stand table prepared is unlikely to be very useful in modelling the forest estate.

The simplest approach will be to prepare average stand tables for groups of PSP's and this can be done during the latter stages of the project. This is the methodology recommended by Andel (1993). Initially PSP's can be grouped by the ODA classification, and Andel recommends grouping into plots that have changed and not changed. The usefulness of this approach cannot be assessed until the PSP data base entry and validation phases are complete.

This should be the first stage in the analysis. It is expected that for much of the Sundarbans forest the diameter distribution may be multimodal and not unimodal, and thus great care must be taken.

If time permits the approach might be extended to fit a Weibull distribution to each species in each plot in turn, but it would be necessary to spend some time investigating the data to determine whether or not it is appropriate, and to assess which parameter estimation method should be used.

Any stand tables that are developed should also have equivalent stock tables prepared as the necessary ancillary procedures are available.

REVIEW OF PROGRESS WITH UPDATING FOREST AND VEGETATION MAPS

The Sundarbans are divided into 9 blocks and 55 compartments, and there have been many different suggestions as to how the SRF may be stratified to best effect. What is the appropriate basis for the preparation of forest and vegetation maps? The real difficulty is that there is not one single stratification that can meet all objectives. There needs to be a number of alternative stratifications based on various levels of resolution and based on varying criteria depending on the way in which each particular stratification is to be used.

The common threads that seem to exist throughout all discussions about how to stratify the SRF are the recognition that change is occurring, that change seems inevitable, that the changes are occurring frequently, and that there are many different possibilities for defining a useful stratification including major species of the vegetation, soil salinity, and Sundri top-dying proportions.

It seems neither possible nor sensible to rigidly define a stratification, as any single stratification seems immediately to attract a multiplicity of arguments about its appropriateness.

However for this project a stratification was required, and item 3 of the TOR includes reviewing progress made with updating the forest and vegetation maps.

The Cartographer Mr F.I.Khan was appointed in March 1994 and is currently preparing the maps. Early progress was discussed with Dr G.Grepin and Mr P.deV.Moss, and the work programme was the subject of a number of back-stopping missions by Dr M.Runkel. It was very pleasing during the later missions to see the considerable progress that has been made. Little time was spent on this aspect of the TOR as Dr M.Runkel arrived in Khulna at the end of the second mission and again during the fourth mission and he has effectively provided the technical support for this activity.

The coverages that have already been prepared include the following.

- Base map.
  - International and SRF boundary.
  - Double sided hydrology.
  - Single line hydrology.
  - Combined hydrology and river names.
- Approximate location of Forest Department stations and offices.

- Topographic sheet index
- Latitude/longitude grid.
    - One minute grid.
    - Two minute grid.
    - Five minute grid.
- PSP location coverage.
    - Approximate locations.
    - Location as remeasured by Dr A.Karim.
- ODA sample plots and incidence of Sundri top dying.
- Wildlife Sanctuaries.
    - Existing.
    - Proposed by Forest Department.
    - Proposed by Dr K.Tamang.
    - Proposed by Dr G.Grepin.
- Administrative boundaries.
    - Compartment boundaries.
    - Block boundaries.
    - Range boundaries.

Coverages currently being prepared include the following.

- Vegetation.
    - ODA 1985 map.

Coverages that remain to be prepared include the following.

- Administrative boundaries.
    - Working Circle boundaries.
        - Sundri.
        - Gewa.
        - Goran.
        - Golpatta.
        - Hantal.
- Zone Maps.
- Sundri top-dying.
    - Repeated surveys in the future.
- Aerial photograph index.
- Fisheries.
- Soils.
- Hydrology.
    - Navigable channels; by depth, but also perhaps by craft, fishing boat, trawler, and country boat.
- Salinity surveys.

The digitising of the ODA coverage is an extremely large and complex task and work is proceeding. Dr G.Grepin is also reviewing progress on this task during his second mission to the Project.

The original intention seems to have been to use the GIS to evaluate changes and differences between successive past mapping efforts, and to continue this approach using SPOT or other imagery in the future. However registration of various coverages will be extremely difficult because of the lack of suitable control points that are known not to have shifted over the years with accretion and erosion. The Hydrologist, Mr S.M.Wahid, has found a small number of survey markers, but these would need to be demarcated so they can be used as control points. Even if such overlays could possibly be carried out with great accuracy, the question would arise as to whether the differences were errors in the coverages being analysed, or reflected the natural changes in the position and shape of the water courses, the object of the exercise. The PC version of Arc/Info is limited by it's inability to "rubber sheet" alternative coverages and this task will have to be carried out elsewhere.

An estimate was suggested that the average erosion and accretion rate may be 1-2 m per year with the maximum as high as 6-10 m. As has been mentioned earlier in this report this erosion, accretion problem alone may have a considerable effect on the calculation of the Annual Allowable Cut (AAC) that has not been considered in the past.

A further difficulty is that the complex vegetational mosaic appears to require extremely high resolution mapping as the forest is composed of very small patches. It is quite possible that these patches are too small for conventional mapping. Patch sized could be investigated by a uniformity trial which would indicate the best spatial resolution for mapping.

For example Golpatta is distributed as narrow bands along the various watercourses and is very discontinuous. It is almost impossible to map at any reasonable scale. The area of Golpatta is quite large, and the economic utility of this species great. If broad strata are defined, including a number of quite discrete ecological types including Golpatta and trees, then the proposed TSP system would allow proportions of each type to be determined and reasonable area estimates made, without the need for formal Golpatta mapping.

Discussions with Dr G.Grepin suggests that the Institut de la Carte Internationale de la Vegetation at Toulouse, France, have worked on this forest as part of a study of cyclonic storm effects on coastal mangrove forests. They believe that this complex mosaic in the Sundarbans is extremely difficult to interpret. Aerial photography is not much better. Apart from patch size, part of the difficulty is that within the one species in a forest type, patches of trees may have full crown, other patches may have dying leaves and others may have new crowns.

In these circumstances the preparation of a vegetation map of the Sundarbans is a difficult task. Discussions about forest planning needs suggests that other approaches may be more appropriate and a possible methodology for the future is suggested in a later section that utilises a TSP and PSP based system. If this is the real situation then detailed vegetation mapping may not be such a high priority and a relatively simple mapping level may be more appropriate. However the new aerial survey that was flown in February 1995 could facilitate a more detailed mapping of some areas, for example Sundri top-dying areas. However Dr G.Grepin (1994) suggests that this 1/15000 panchromatic aerial survey may not be sufficient. He recommended that colour photography rather than black and white be used and that the area be flown at 1:7500 as he considers that this will be far more effective in mangrove forest. However the area has now been flown.

A major difficulty is that even in late April 1995 this latest aerial photography had not been made available to project staff in spite of repeated requests.

The Geographic Information System (GIS) provides a very effective means of storing the various coverages, but does not provide the technology for analysing remotely sensed imagery. A system such as LARST (from the Natural Resources Institute ODA) can provide access to local satellite reception and relatively simple processing of that data. This would complement a system such as MicroBrian which would utilise other commercially available imagery such as from Landsat TM and SPOT. It would also be highly desirable to acquire a good raster-vector analysis system such as Spans from Intera Tydac. This is because Arc/Info is less efficient in analysing overlays, but is very satisfactory for maintaining the polygon data bases. These acquisitions will not be necessary for the current project but will be highly desirable for the ultimate implementation of an ongoing forest monitoring system for the SRF, perhaps through the planned Operational Unit (OPSUNIT).

During the third mission the Cartographer was requested to carry out a number of analyses. A map was prepared of the PSP locations, showing whether they had been measured or not. The complete PSP coverage can then be intersected with a stratification coverage to prepare a list of PSP's that are in a particular stratum. These lists are the basis for the calculation of strata averages within the IDB. A further analysis intersected one, two and five minute grid coverages to determine the number of intersections that fall on land, on water, or on a 100 m wide buffer either side of the boundary. This information is necessary for determining the ideal grid structure for the TSP's proposed in the next section.

A PROPOSED METHODOLOGY FOR THE FUTURE

The project has identified the preparation of the IRMP as a primary objective and, in terms of forest management inventory, growth and yield, the information that it is feasible to provide for inclusion in the IRMP during this project is extremely limited both in scope and precision.

Part of the implicit TOR is to provide a soundly based direction for the future. Care has been taken to ensure that the work carried out fits within a satisfactory framework for the longer term. It is necessary to describe a framework that it is believed will provide the required information for the future management of the Sundarbans in a cost effective and efficient manner.

Integration with other Projects

At the end of the first mission discussions were held in Dhaka with the then Chief Conservator of Forests, Mr Muzammal Hossain, and also with the Conservator of Forests and Project Director of the Forest Resources Management Project (FRMP), Mr Noor Muhammed Sarker. There is a need to ensure that this project coordinates activities with the FRMS project and that both work together to ensure the integration of planning in the future.

Unfortunately it was not possible to discuss these issues with the Officer in Charge of RIMS (the Resource Inventory Monitoring System) Dr Ishtiak Uddin Ahmed until brief discussions were held at the end of the second mission. The planned revision of RIMS will parallel some of the developments in BGD/84/056 and the revision is expected to be a simulation model in order to provide more flexibility, and it is expected to interface with a GIS. The linkages between the project and the RIMS/FRMP team need to be fostered as both will eventually need to be integrated. However the Sundarbans is such a complex, integrated ecological system that it may possibly need to be considered as a special case, and only relatively simple linkages established to other projects.

At the end of the third mission discussions were held in Dhaka with the Chief Conservator of Forests, Dr Shamsur Rahman, who accepted that it would be highly desirable for these integration issues to be discussed very widely. It is important that each unit does not operate in isolation. Discussions are also planned for the end of the last mission.

Philosophical Basis

The problem of the continued monitoring of the Sundarbans seems to resolve itself into two issues:

- the need to be able to apply any stratification at any time, and,
- the need to determine changes at intervals of less than the current 10 years or so, preferably every year,

and it is highly desirable that any future system meets these needs.

Past surveys in the Sundarbans have been based on stratified random sampling, with the area being mapped and stratified prior to the establishment of plots. The design was based on the known statistical efficiency of stratified random sampling (eg Leech and Correll 1993). This generally has economic advantages but requires that the stratification be carried out prior to plot measurement, that the stratification be accepted as appropriate, and that it does not change over time. These requirements are not believed to be appropriate for the management of the Sundarbans.

The advent of the Geographic Information System (GIS) now allows a far wider range of alternative stratifications to be assessed and analysed, unlike previously when it was generally only feasible to use one particular stratification. What is needed for the future is the ability to carry out stratification and plot measurement completely independently and then, in the analytical phase, to extract the data from a data base for any particular stratification that is required for any aspect of forest management planning.

Further, the cost of collecting data is so great, especially in the Sundarbans, that there is a requirement for data collection to be integrated so that measurements are not repeated for different scientific and forest management uses.

Another important issue is that good growth models and other mensurational models can only be developed on very accurately measured data that cover a wide range of silvicultural conditions, far wider than occurs naturally in the forest. Experience suggests that accurate remeasurements on 100 permanent plots provides more information for growth and yield modelling than 1000 inventory plots measured to a lesser precision. Sound model development based on accurately measured plots is absolutely essential if the models are to be effectively extrapolated and alternative silvicultural management regimes evaluated. A plot system that can be used for these purposes will be a biased sample of the extant forest conditions.

In essence there is a need for two types of plots not one.

- A PSP system that would provide data for the development of models. The number of plots need not be great, but the plots should be sited so that they are uniform, and the range of conditions should cover the complete range of forest conditions. Research trial plots can be measured to similar standards and these can be used to augment the PSP data base and provide data extrapolating stand conditions outside the usual range. Ingrowth or recruitment models and mortality models can be developed on these data.

- A TSP system that would then provide estimates of the current status of the forest at any point in time. Like the PSP's, these would be stored in the Integrated Data Base. The plot locations would also be stored as a point coverage in Arc/Info.

To get mean strata statistics (such as stocking and volumes) for any area of interest the method is to prepare the stratification that is desired. determine which TSP's occur within each of the strata. then combine the plots for each strata to determine strata mean statistics. The approach therefore allows the TSP measurement to be completely independent of the stratification.

Temporary Sample Plot Sampling Design

If the TSP's are established then it is necessary to ensure that the complete area is covered. It is necessary to define a sampling framework.

Basically the alternative approaches are:

- simple random sampling,
- stratified random sampling, and,
- systematic sampling.

If a systematic sample is used then the whole area is evenly covered and, provided that there are a reasonable number of TSP's in each strata, then good strata mean estimates can be obtained. However there is a chance that for a particular stratum there may be no TSP's present, or too few TSP's, which can cause difficulties with an analysis. By strict statistical standards there is a likelihood that some strata will be relatively over sampled, but given the likely range of stratifications to be evaluated for the Sundarbans this is unlikely to be a serious economic disadvantage.

The advantage of stratified random sampling is that all strata are sampled and, more importantly, fewer plots need to be measured to gain a particular precision level than with a systematic sample. Theoretically it is economically more efficient. The difficulty is that it is necessary to carry out the stratification before any TSP's are measured, and this is considered ill advised for the management of a dynamic ecological system such as the Sundarbans where changes are occurring quite rapidly.

A simple random sample could be used but this is likely to provide a clumped distribution of plots geographically and is not likely to be satisfactory in practice.

The most appropriate solution is considered to be a systematic sample. Although strict statistical precision levels cannot be obtained for a systematic sample, Prof B.Matern (1947, 1960) has determined a method that has been used to determine precision levels in Myanmar. Dr B.Ranneby at Uppsala in Sweden has also worked on this problem more recently (1981). Experience in Myanmar demonstrated that for two example areas the Matern method of calculating sampling precision matched the precision based on the assumption that the systematic sample had actually been a simple random sample. In practice, such eminent sampling theory statisticians as Prof T.Cunia do not seem to believe that there is a problem; he designed the systematic sampling procedure implemented in Myanmar. I feel sure that Prof Cunia would recommend a systematic sample under the circumstances in the SRF!

There is a further advantage. If plots are established such that an equal proportion is established each year, say 400 per year over a five year measurement cycle, then by careful location of the grid cells to be measured each year, a very good estimate can be obtained each year into the future. Because only 20% of the plots are replaced each year any changes may take some time to appear but annual trends do become evident, even though plots are only remeasured every five years.

One way of laying out the plots for each of the five years of the measurement program could be as follows. with 1-5 representing the grid cells to be measured in each of the first 5 years of the inventory. In the sixth year the plots measured in the first year would be remeasured. Thus inventory becomes a continuing annual exercise and can readily be planned as an ongoing activity. This would have the advantage of facilitating the establishment of a forest mensuration or measurement section, with appropriate staff, facilities. and budget line items, and would be a continuing activity ratner than a project by project operation. This would enable mensuration standards to be continually improved and maintained at a higher level than is possible at present.

More efficient designs are possible by applying adjacency constraints.

1	3	5	2	4	1	3	5	2	4	1	3	5
3	5	2	4	1	3	5	2	4	1	3	5	2
4	1	3	5	2	4	1	3	5	2	4	1	3
2	4	1	3	5	2	4	1	3	5	2	4	1
5	2	4	1	3	5	2	4	1	3	5	2	4
1	3	5	2	4	1	3	5	2	4	1	3	5
3	5	2	4	1	3	5	2	4	1	3	5	2
4	1	3	5	2	4	1	3	5	2	4	1	3
2	4	1	3	5	2	4	1	3	5	2	4	1
5	2	4	1	3	5	2	4	1	3	5	2	4
1	3	5	2	4	1	3	5	2	4	1	3	5

It is believed that if this type of design is implemented that it will be possible to better monitor the ecological evolution of the Sundarbans and it will also provide a basis for forest management that can effectively utilise all the latest available information.

The actual systematic sample design should be considered in more detail than has been possible during these missions, and should be subject to input from a number of other people from outside the Project. It could perhaps be the subject of collaboration with a University, or with BFRI, or perhaps be the subject of a backstopping or another FAO mission, and must be compatible with planned Forest Department inventories elsewhere.

It is suggested that the design could be along the following lines.

- Primary locations at intervals of 1 minute. This has the advantage of being directly transferable to SPOT imagery for field use to assist plot location. An analysis by the Cartographer. Mr F.I.Khan, showed that there would be approximately 1900 primary locations of which approximately 1250 are expected to be on land, 600 on water, the remainder being indeterminate. Approximately 2000 sites would need to be surveyed to ensure that all TSP sites are measured.
- Each Primary Site could be the centre of a 3x3 or 4x4 grid cluster of sub-plots, or probably better, a cross shaped line of 7 or 9 plots, each sub-plot separated from each other by say 50-100 m.
- Sub-plots could be 10x10 m (0.01 ha) up to 25x25 m (0.0625 ha) in area. They should probably be square to provide the greatest homogeneity.

Another alternative design would be to measure only one plot, probably at least 30x30 m in size. This would be simpler and may be more appropriate for non wood measurements.

Another option would be to have a central larger plot with small satellite cluster plots for some attributes.

TSP Measurements

Because each TSP would be established at a particular location and should not be shifted to make it uniform. unlike the PSP's which have been established as uniform plots, it will be necessary to subdivide the TSP into mappable sub-plots of different ecosystem types.

This must be reviewed in detail but the suggested ecological types could include the following.

- Mangrove Forest,
  - Sundri,
  - Sundri-Gewa,
  - Gewa,
  - Keora, etc.,

  using the same forest type codes as exist in the PSP data base.
- Golpatta,
  - Golpatta-tree mixtures,
  - pure Golpatta.
- Grass,
  - by species,
- Water.
- Inter-tidal zone.

Each sub-plot could be mapped into 2x2 m or 3x3 m recording units and the data recorded for each of these recording units. Each of these recording units would be considered uniform. This would enable estimates to be made of the proportions of each TSP that occur in each forest type category and so would allow a good estimate to be made of the area of Golpatta, which is extremely discontinuous and occurs in small bands. It would also allow an estimate of water within the land area. Care will have to be taken to ensure that the TSP's cover the complete area as the TSP system must be compatible with the GIS. It will be essential to record all TSP sites even if they fall completely in water.

It would also be necessary to record the forest type that the plot or sub-plot should be considered representative of, since it may not be sensible to derive the forest type from the measurements of such a small sub-plot.

The measurements to be made on each TSP must be reviewed in considerable detail, but could include the following.

Plot Information.

- Plot key.
  - Nominal location.
  - Exact GPS based location.
  - ODA Forest Type.
  - General Forest Type.
  - Soil type.
  - Map of Ecological Type in each subplot.
  - Distance to navigable water:
    - by fishing boat,
    - by trawler,
    - by country boat.

For each sub-plot and for each recording unit.

- Ecological Type.

- If the Ecological Type is a tree based type.
  - For each tree.
    - Species.
    - Dbhob.
    - Tree health.
    - Crown type.
  - Under storey species.
    - Species.
    - Abundance.
- If Golpatta.
  - For each clump.
    - Clump diameter.
    - Number of seedlings.
    - Number of one year old stems.
    - Number of mature stems.
    - Number of over mature stems.
    - Number of cut stumps.
    - Flowering or not.
    - Fruiting or not.
  - For a sample of clumps.
    - Tallest stem.
      - Height.
      - Number of leaflets.
    - Average Stem.
      - Height.
      - Number of leaflets.
- If the ecological type is water.
  - Turbidity.
  - Salinity.
- Soil information.
- Entomological observations.
- Wildlife observations.
- Accretion, erosion, and sedimentation characteristics.
- A description of the site if the site is, for example, part of a forest station, a fishing camp, a jetty, or whatever. Subjects where the above descriptions do not make sense.

On a selection of sub-plots and/or recording units the following could be measured.

- If the Ecological Type is a tree based type.
  - Number of saplings less than 2.5 cm dbhob, by species.
  - Number of seedlings less than 1.3 m high, by species.

The TSP would provide a focal point for any data collection designed to provide estimates of the current status of any particular parameter or characteristic in the Sundarbans. The distance to navigable water is highly desirable as this parameter is likely to be very useful in the prediction of unofficial consumption, especially firewood collection.

One further advantage of this systematic TSP program is that the program would be an annual program with its own budget line. This would enable the formation of a cadre of experienced, highly trained measurement crews, whicn in turn would result in the data obtained being of far higher quality than can be obtained with one-off inventories.

The advantage of having highly trained, highly motivated staff, to carry out the mensuration cannot be overemphasised. The problems with the data quality of the current PSP remeasurements are in large measure due to the measuring crews lacking sufficient training, knowledge and skills. If a permanent crew is created, at least at the senior levels, then they would become an experienced elite measurement crew. They would be able to assist all other research and monitoring efforts as well as their primary responsibility for PSP and TSP measurement.

However the real advantage of the proposed PSP and TSP systems is that it could ensure that all monitoring work is carried out on the one site, and that researchers do not duplicate measurement effort to meet their own particular requirements. For example if sedimentation traps are to be installed and measured then it makes sense to do it in TSP's, even if not in all TSP's, as then the soil, forest ecology, and forest type have already been recorded and more measurements do not need to be made. The same thing could hold for entomological analyses, Sundri top-dying studies, and so on. The approach provides maximum information with minimum duplication of effort. It is the most flexible approach that seems to make any sense. Other sites may have to be established for particular special purposes, but wherever possible these sites should be used.

Such a broad based, multi-disciplinary TSP system would facilitate the carrying out of multi-variate statistical analyses, such as are in the TOR for the Statistician. One such analysis might assist resolving some of the confusion and lack of understanding of top-dying Sundri, and might identify the variables that occurrence is correlated with, and so might lead to a better appreciation of forest management options.

Some brief discussions were held with Mr A.Mitchell to assist him determine an approximate budget necessary to enable this permanent mensuration crew to be established and maintained. The team would provide the well trained measurement crew that would be able to assist most, if not all, consultants if this project is extended.

TSP Data Storage

Data would be stored by plot, sub-plot and recording unit key, and retrieved as necessary to provide estimates for any stratification. Point coverages of both PSP and TSP plot locations would be stored in the GIS.

In essence the TSP data base stores point estimates and stores no strata areas at all. The area information is external to the TSP system. The strata means would also provide proportions by the ecosystem categories (for example, water, Golpatta and Mangrove) and thus, indirectly, estimates can be made of the area of Golpatta and the area of Mangrove forest in a stratum as proportions of the area for any particular stratification. Analysis can also provide proportions by major species if so desired.

As the TSP's should be located accurately with a GPS, they can provide very useful ground truthing plots for GIS, Image Processing, and other spatial analytical activities.

This is an extension of the Integrated Data Base (IDB) and should be managed by the Operational Unit (OPSUNIT).

Tree Volume Prediction

There are two approaches that should be considered. The first is to continue to develop tree volume equations based on felled sample trees, and this will require that additional data be collected to build on the tree data base that has already been prepared by the project. This is the simpler approach and the one used in classical past forest inventories. It is the approach adopted by this project.

An alternative is to integrate tree volume measurement into the measurement of the TSP's by using techniques such as Importance Sampling (see the references in Leech 1994, a copy of which has been provided to the project). There is little doubt that this approach is more effective and is economically efficient, but the cost savings must be balanced against the increased complexity of the theory, measurement and calculations that are necessary.

PSP's and other Research Plots

The TSP's do not replace the PSP's in any way. The PSP's become a series of intensively monitored research style plots and, if at all possible, any intensive monitoring study should be directed to these areas. The plot system may need to be expanded a little, perhaps by 20-30 plots, so that different silvicultural treatments may be applied to some forest types, and also to ensure a better coverage of all ecosystem types.

The PSP's are used to develop the mensurational models; growth and yield models, ingrowth models and mortality models. The TSP's provide an ongoing inventory of the forest, with the plots always being 1-5 years old, and on average 3 years old. This will be far superior to the current situation where the latest estimate based on a reasonably adequate temporary plot sample is now 10 years out of date. Trends will be evident each year, changes will be gradual, and there will be fewer unexpected surprises for forest managers.

Even the PSP's cannot provide all the necessary models and other mensurational trials will probably need to be established. The most important is to develop models predicting the utilisable volume from the total volume estimate by the TSP's. Larsen (1994) notes the magnitude of the differences, and they are far too great to be ignored. It will also be necessary to develop models to convert from one mensurational metric to another.

The unofficial consumption from the forest may need to be explicitly surveyed to determine its extent. The PSP system will provide an estimate of the minimal levels of consumption, but the more careful control of these sites means that any estimate will be an under-estimate.

It will also be necessary to establish plots in plantations, and to carry out silvicultural research on these plantation areas so that future management options can be better evaluated.

Suggested Planning Subsystem

One simple structure of the information flow for the Planning System such as this is detailed in Appendix 2b in the form of a Data Flow Diagram (DFD). It was not possible nor sensible to provide any more detail in the available time, but this structure can be used as the basis for a much more detailed design if the proposal is accepted.

The essential criterion in the systems analysis design phase of this project is to maintain the independence of the various data bases, and also the tree volume equations, diameter growth models, volume based growth and yield models, and most importantly, the stratification. The system requires complete, integrated, top down systems analysis, concentrating on the flow of data through the system.

The PSP data base has been discussed earlier in this report and the modules necessary are shown on the first page of the DFD in Appendix 2b.

These data are the primary source for the development of the various statistical models, which in the immediate phase will be restricted to the development of tree volume equations, height diameter, and diameter increment models.

The tree volume equations should be coded in a separate data base format for most flexible use. A number of different sets of equations can be prepared, initially two sets, the equations about to be developed and the ODA equations. The data base structure could be:

- Key number,
- Species,
- Ecological zone number (an optional key, not used initially, such as ODA forest type, the stratification, if any for equation development),
- Equation type,
- Number of parameters,
- Parameters (up to 7-10), eg b1, b2, b3 ...b10.

The data base structure should be generalised so that the same structure can be used for any equation, and a procedure developed which calculates Y from X using a particular file and key. One way of setting up the equations, that covers most of the forms reported in this and other reports, could be as follows:

01	$Y = b1 + b2 * X + b3 * X^2 + b4 * X^3 + ...$	
02	$Y = b1 + b2 (X ** b3)$	
03	$Y = b1 + b2 / X$	
11	$Y = exp(b1 + b2/X)$	
12	$Y = b1 \{[1.0 - exp(-b2 * X)] ** b3\}$	
21	$Y = exp(b1 + b2 * X + b3 * log(X))$	if $X<=b4$
	$Y = exp(b1 + b2 * b4 + b3 * log(b4))$	if $X>=b4$
22	$Y = b1 + b2 * X + b3 * X^2 + b4 / X$	if $X>=b5$
	$Y = 0.0$	if $X< b5$
51	$Y = b1 + b2 * X1 + b3 * X2 + b4 * X1^2 + b5 * X2^2 +...$	
52	$Y = b1 + b2 * (X1 ** b3) * (X2 ** b4)$	

Equation 21 is the ODA equation, with the (b4) parameter included so that the maximum diameter can be set. If there is no maximum diameter specified, as occurs for some species, then (b4) can be set to some large number. Equation 22 is the format of the tree volume equations for Gewa defined earlier in this report (note that b2=0). Some switching of parameters will be necessary to get the equation file set up properly with these generalised forms.

Note that equations with more than one variable can be represented as equation types 51, 52 and so on. Equation 52 is the generalised combined variable tree volume equation form.

This methodology will provide a flexible approach for equations to be built into the various calculation procedures. It can be expanded as necessary.

Then, a stratification of the forest must be prepared. This could be the existing ODA stratification, or any other stratification determined in any manner, including the GIS. Then for each stratum a list of plots is prepared, and this can be prepared either by hand or by the GIS. This file should include:

- Stratum number,
- Stratum area,
- List of plots in each stratum.

The user of the system must ensure that each stratum has at least a minimal number of plots, or the stratification must be changed. This can be automated with an Arc/Info SML (written in Arc Macro Language, the PC version of which is called SML or Small Macro Language).

The system would then extract these plots and prepare the necessary stratum averages across these plots.

Initially a simple approach can be used and the plot list can be prepared by hand. It will be necessary eventually to use the GIS to prepare the stratification and plot list.

This plot list becomes the basis for the extraction of the plots to be summarised.

Tree diameters are extracted for each species from each plot and the appropriate tree volume equations used to prepare tree volume estimates. These can then be totalled by species within each plot, and then across all the plots to provide the necessary stratum estimates. This sounds simple but experience suggests that programming this stage is complex and will take longer than expected.

The next step is to build a system to permit growth models to be built into a strata mean projection model. This will be faster to process on PC's than a model aimed at growing individual plot data. It will require that a future management regime must be defined. The outputs will generally be quite stable and can be defined relatively simply.

This management prescription could be as simple as harvest from particular compartments in particular years, specifying species, diameter and growth category limits for extraction.

The system is in essence a simulation model of the forest. It can be used to predict what the forest estate is likely to be assuming the current silvicultural managèment regime continues to operate. It can also be used to assess alternative silvicultural and management options and so allow sensitivity analyses to be carried out that will lead to improved integrated forest management practices being adopted.

The system will not be a static system that is developed and never changes, but must be a dynamic system that will continually be modified as new growth, yield, mortality and recruitment models are developed, and as new multiple-use needs emerge. The system will evolve over time and prediction precision will continually improve. This will require that a team be assigned on a continuing, ongoing basis. It cannot sensibly be carried out by a project with finite deadlines to meet unless those project staff can also be assured of continuing on the tasks after project completion. This is the task of the Operational Unit.

System Outputs

The system can be used to prepare a number of separate estimates, depending on what information is needed at any particular time. The system is designed to be as flexible as possible, relatively easy to implement, to be expandable, to be upgradable, and to meet the expected needs for the effective management of the SRF.

Estimates can be made of the standing growing stock for any stratum, or part of the forest, or for any TSP, by species, in terms of stocking, basal area, and volume to any particular utilisation or size class.

Care must be taken not to over-stratify and to ensure that each stratum has sufficient TSP's within it so that estimates can be made efficiently and effectively. Strata areas can be determined.

Analysis of the TSP data will provide estimates of mortality, of changes in Sundri top-dying, of recruitment and of both official and unofficial consumption.

The stratum averages will also be input into a simulation model that also takes growth models, recruitment models, unofficial consumption models, and a plan of official consumption, and prepares for each year into the future estimates of what is likely to be extracted and what the residual status will be of the future growing stock. It is a mathematical simulation of the forest processes.

Various runs can be carried out with different assumptions about growth models, inventory, unofficial consumption levels, and planned operations, to determine expected outcomes for a particular set of options. The Forest Department would then be able to inspect the outputs from a series of alternative computer simulation runs, could determine which management option is the preferred option, and could set its management objectives accordingly.

This process would completely replace the current methodology for determining the AAC (Annual Allowable Cut) and it would also change the base from a pure area calculation approach to one that is primarily based on volume but also takes into account other aspects, including area control, salvage felling and so on. This would facilitate an improvement in planning.

The estimates will be imprecise at the early stages of full implementation, but analysis of the analyses will demonstrate where the weaknesses are in data and models, and then these can be progressively refined so that the data and totally integrated system continue to improve.

The likely major sources of bias and imprecision for the initial estimates include the following.

- Measurement errors in both TSP's and PSP's, especially the past measurements.
- The tree volume equations used to determine volume from diameter (and possibly height and other site variables).
- The utilisation assumptions made. The models that convert true volume to utilisable volume.
- The models of unofficial consumption.
- Errors in area determination.
- The representativeness of the plots for the stratification. Are there sufficient plots? Are the plots truly representative of each stratum? A large systematic sample will help avoid these problems.

The objective has been to design a framework that can meet the expanding and changing needs for management of the SRF into the future. This project is one step along the way.

Integration Issues

A Geographic Information System (GIS) has been acquired to facilitate mapping and analysis. The Arc/Info system from ESRI is a very satisfactory vector based GIS and it is critical to the success of the project.

The proposed PSP and TSP calculation systems are designed to effectively integrate with this GIS technology to provide better integration of planning. This integration has successfully been carried out by this Consultant both in Australia and Indonesia. The integration will require considerable care to ensure that the data flows between the Integrated Data Base, with its PSP and TSP subsystems, and the GIS, are effective and efficient.

The more important issue is to ensure that the planning system is integrated by the Forest Department into the management of the Sundarbans. The system does not make any management decisions at all, just allows the Forest Department to make better decisions based on better information. The system is just a tool to assist the Forest Department improve the management of the Sundarbans.

Acquisition Issues

A system of this size can effectively be implemented on any reasonably sized 80486 DX or larger PC. The data bases will become quite large. So larger hard disk storage devices will ultimately be required, but not during developmental stages.

It would be desirable for a backup device to be acquired such as a cartridge backup system. The Colorado Trakker Tape unit operates from the parallel port and enables 205 mb of data to be stored on one cartridge. Backups should be taken regularly and stored at a number of alternative sites. This device would cost about $US 400, and cartridges should cost about a further $US 20 each.

The Geographic Information System (GIS) provides a very effective means of storing the various coverages, but does not provide the technology for analysing remotely sensed imagery. A system such as LARST (from the Natural Resources Institute ODA) can provide access to local satellite reception and relatively simple processing of that data. This would complement a system such as MicroBrian which would utilise other commercially available imagery such as from Landsat TM and SPOT.

Arc/Info is a vector based system and is not ideal for analysis of raster based images. It is suggested that for any extension of this project's operations a PC based package Spans, available from Intera Tydac Inc., be acquired for just this task. This package uses a quadtree approach and appears mathematically to be the most efficient package for overlay analysis. It was acquired by the Indonesian National Forest Inventory to interface between their workstation based GIS and Image Processing System components, although it has yet to be used to its full capacity.

Summary of Proposal

This proposed monitoring procedure breaks the nexus between stratification and plot measurement and allow the two aspects to proceed independently.

The systematic sample ensures that the Sundarbans are completely covered. A cluster approach would allow within and between plot variation to be determined. The TSP and PSP systems can very effectively be integrated with the GIS.

Changes can be reported annually and so trends will become evident earlier, and unexpected results will be far less likely to occur. It will provide more timely reporting of changes than is currently possible.

However it will be essential for the Operational Unit (OPSUNIT) to be formed so that these activities can all be strengthened. This will need considerable further training in forest mensuration, in computer systems analysis and programming, in biometrics, in the GIS, in many other disciplines as well, and also in the use of this integrated information resource to assist strategic and management planning across all concerned agencies.

OTHER ACTIVITIES

There were a number of other activities carried out during the various missions at the request of the Officer in Charge.

Spotted Deer Simulation Program

A program was written in FORTRAN to determine the maximum sustainable yield (MSY) of Spotted deer (***Axis axis***) given particular parameters. The algorithm was based on Grimsdell and Bell (1975) for Black lechwe in Africa. The parameter estimates used were based on Tamang (1993) and other estimates provided by the Officer in Charge (Mr Peter de Vere Moss pers.comm.). The program can readily be modified to indicate the effects of changing particular parameters.

Efforts are being made to obtain the necessary parameters so that an evaluation can be made of the maximum sustainable yield of Spotted deer that might be harvested.

It is planned to use the same program to determine the MSY for other wildlife populations, such as wild boar. It is planned to incorporate the simulation results into the wildlife component of the IRMP.

Miscellaneous

Various draft reports and reports were reviewed at the request of the Officer in Charge.

During the third mission a technical appraisal was prepared at the direction of the Chief, Asia Pacific Desk, FODO, of the Statistician's work output.

Assistance was given to Mr B.C.Sarker in the preparation of a document summarising the Permanent Sample Plot measurements.

The fourth mission was largely spent writing draft segments for incorporation into the IRMP and in ensuring that the best available information was used for the preparation of the plan.

SUMMARY

The four missions have successfully achieved the major objectives in spite of the minimal time frame and the difficult working environment. This was in no small part due to the great cooperation received from the Officer in Charge Mr Peter de Vere Moss and all the staff of the Project. The particular efforts of Mr Andrew Mitchell and Mr B.C.Sarker were especially appreciated.

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APPENDIX 1: Terms of Reference

BANGLADESH

INTEGRATED RESOURCE DEVELOPMENT OF THE SUNDARBANS RESERVED FOREST

(BGD/84/056)

TERMS OF REFERENCE CONSULTANT ON MANGROVE INVENTORY

Under the supervision of the Director, Forestry Operations, and with the support and guidance of Technical Support and Operations Officers and the close supervision of the Chief Technical Officer and in consultation with other project officers, the consultant will perform the following tasks:

1. assist the project team in reviewing and analysing the progress made with the processing of the PSP data from the Sundarbans area;

2. based on the above outcome, recommend appropriate implementation schedules and methodologies for the elaboration of: growth and yield studies, forest site and compartment classifications and provisional stand yield tables;

3. review with the project team the progress made with up-dating (based on 1990 air photos) of the forest and vegetation maps of the Sundarbans;

4. assist the project in establishing working linkages with the inventory component foreseen under the World Bank financed FRMP, according the progress of the latter;

5. assist the project team in reviewing and analysing the progress made by the project in the preparation of an integrated forest management plan for the Sundarbans;

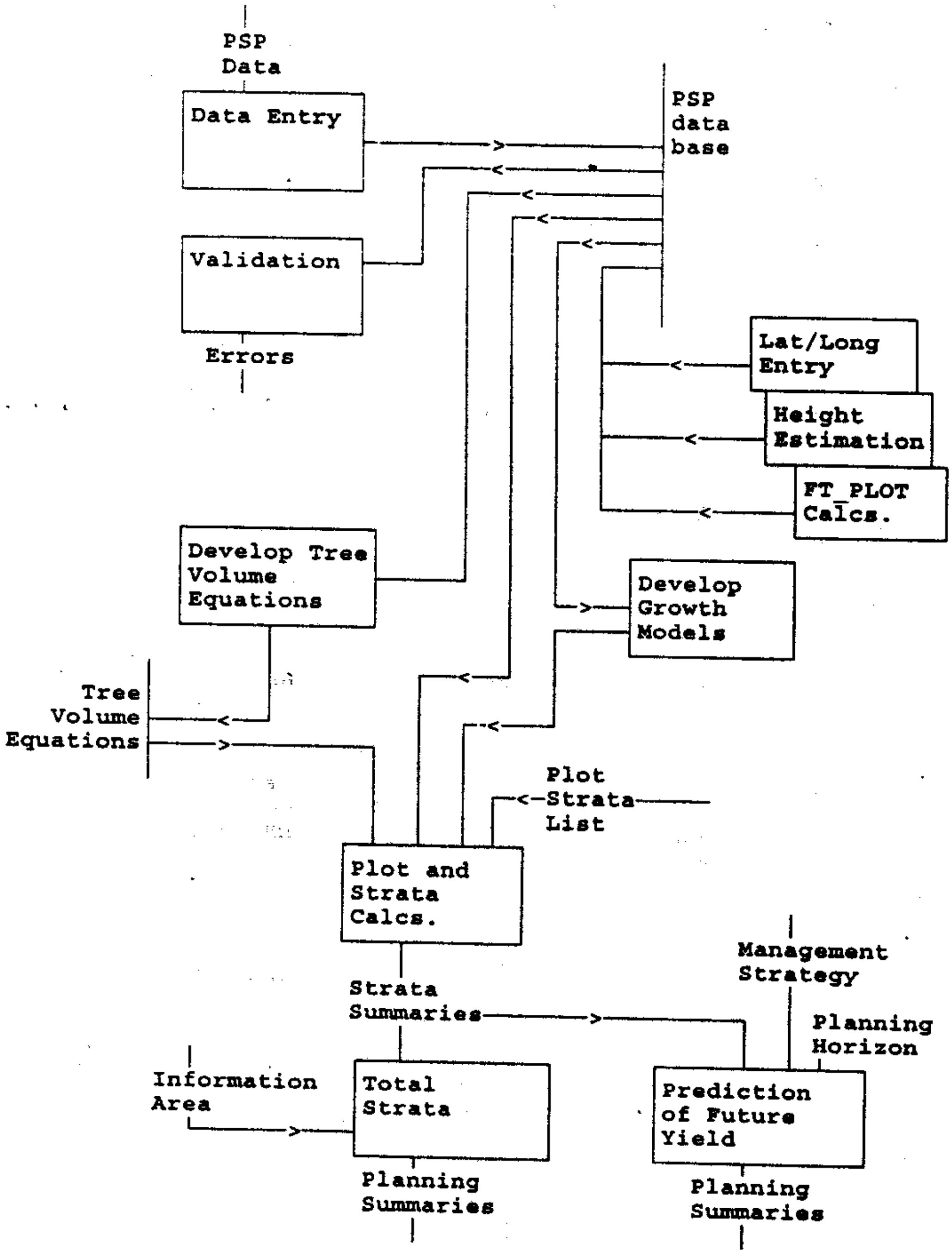
6. prepare a report including findings and recommendations which should be discussed and cleared with the Government authorities concerned before departure from the country; the consultant will then present the report to FAO headquarters (within one month of leaving the country), and will amend it in light of comments received.

Duty Station:	Khulna, Bangladesh
Duration:	3 weeks with briefing and debriefing in Rome
EOD:	Soonest 1993
Language:	English

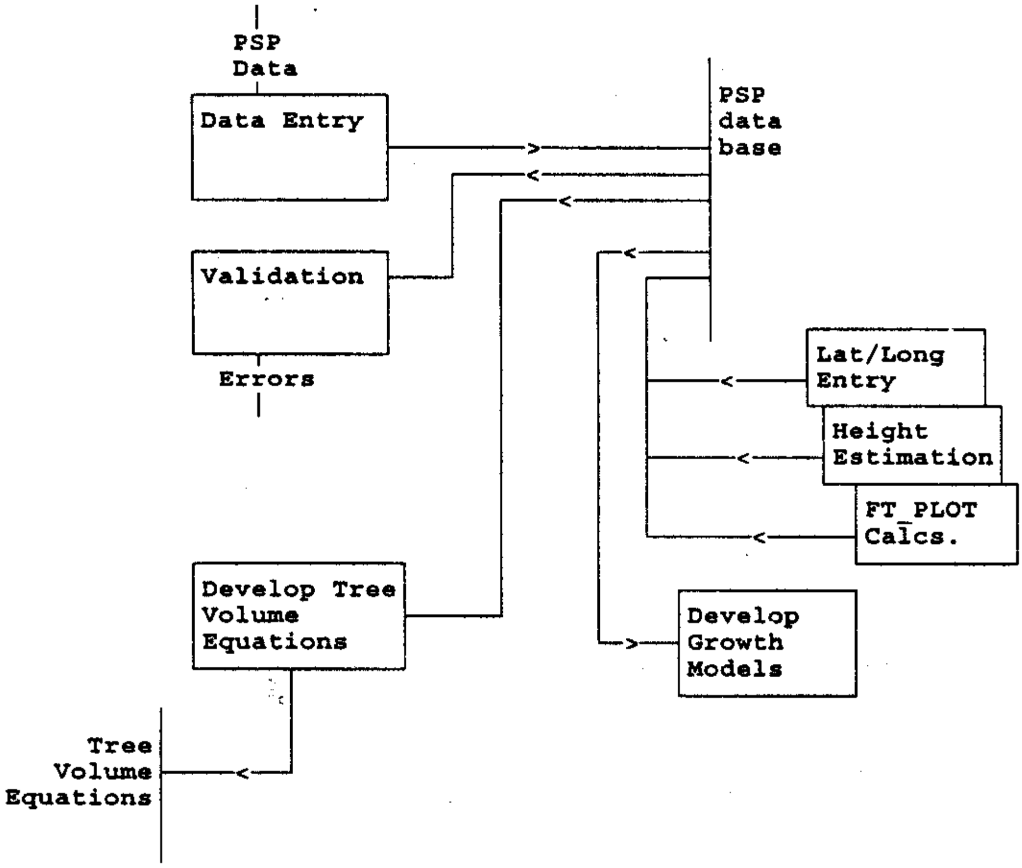
modified subsequently to:

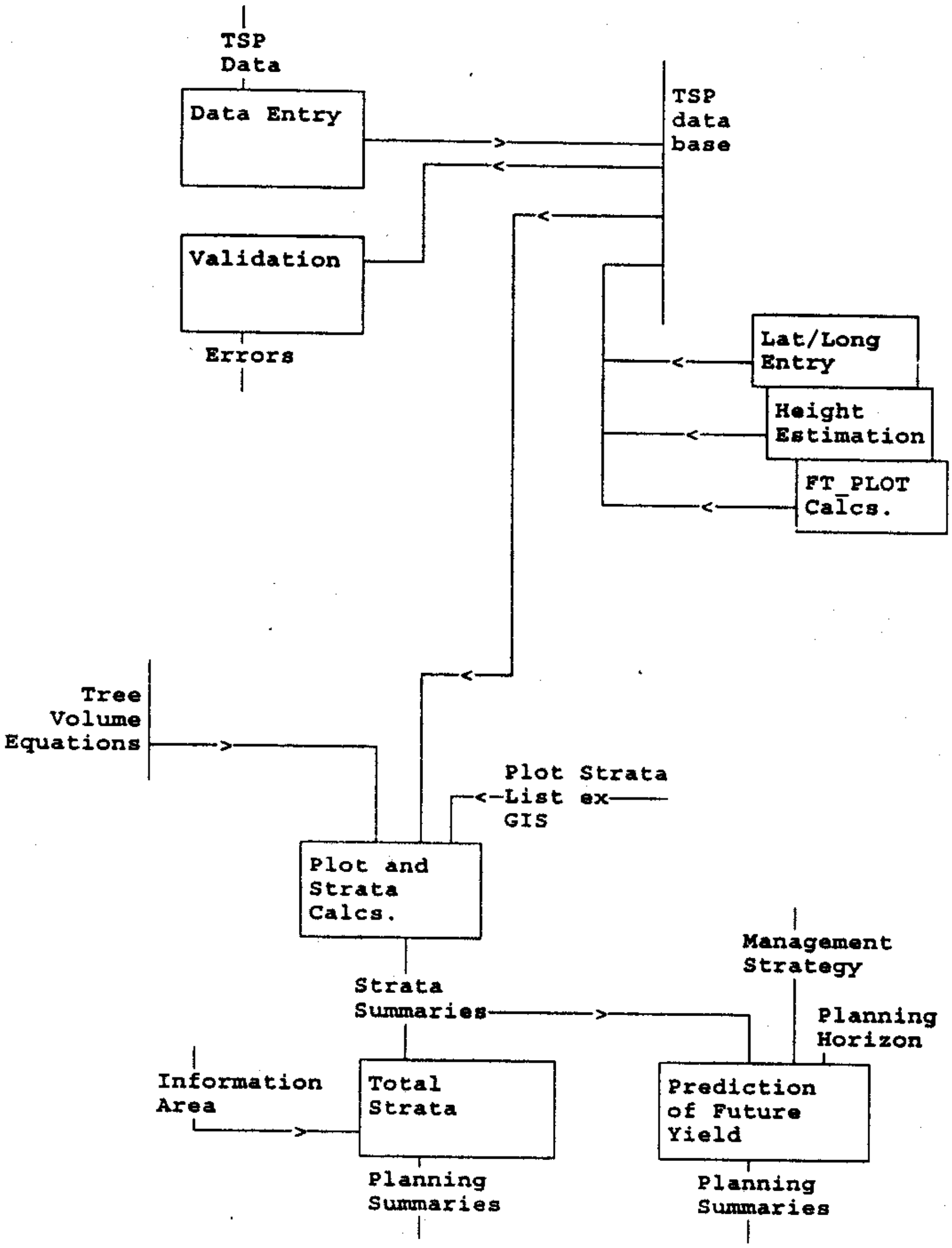
Duration:	2 weeks (items 2 to 5)
EOD:	April/May 1994

APPENDIX 2a: Data Flow Diagram for the Proposed System using PSP's alone



APPENDIX 2b: Expanded Data Flow Diagram for the Proposed System using PSP's, TSP's and the GIS





TSP Data
Data Entry
TSP data base
Validation
Errors
Lat/Long Entry
Height Estimation
FT_PLOT Calcs.
Tree Volume Equations
Plot Strata List ex GIS
Plot and Strata Calcs.
Management Strategy
Strata Summaries
Planning Horizon
Information Area
Total Strata
Prediction of Future Yield
Planning Summaries
Planning Summaries

APPENDIX 3: Sundri Tree Volume Equations

This report on tree volume equation preparation was originally prepared in great haste during a Hartal late in the second mission in December 1994, and it took a great deal of dedicated effort by Ms Shubhra Farzana and Mr B.C.Sarker to provide the data in time to even carry out these analyses. Because the data were produced in such haste some errors were discovered in the data base provided. The data base has since been corrected and the models have been recalculated.

The data are still not completely satisfactory and are limited in extent, so the models must be used with considerable care.

The results provide some disturbing indications about the ODA equations which were possibly based on more data. It is considered that these new equations provide a better base equation for predicting Sundri tree volumes.

After this final report has received technical clearance this appendix will be extracted as a separate report and submitted for publication in an appropriate technical journal. This paper should be seen as a joint report as it has been a joint effort and not the work of any one individual.

The following files were left with Mr B.C.Sarker:

- Linear models
  - VOLS.INP — The modified input data file.
  - VOLS.GLM — The GLIM input code.
  - VOLS.OUT — The output from running GLIM with the file VOLS.GLM and data VOL.INP.
- Nonlinear models
  - SUNDRI.VOL — The modified input data file, to be copied to FOR002.DAT.
  - SUNDRI.001 — The NLPE control input data file, to be copied to FOR001.DAT.
  - SUNDRI.FOR — The FORTRAN code for subroutine DLSQ.
  - SUNDRI.001 — The output from running NLPE for the model with D alone.
  - SUNDRI.OU2 — The output from running NLPE for the model with D and H together.

PRELIMINARY OVER BARK TREE VOLUME EQUATIONS FOR SUNDRI

by

J.W.Leech, A.Karim and B.C.Sarker

Abstract

Tree volume equations are presented for Sundri growing in the Sundarbans, Bangladesh. These equations are based on limited data but are shown to be better than the equations currently available for this area.

INTRODUCTION

The mangrove forest of the Sundarbans is diverse and slow growing, and is extremely important economically to Bangladesh. Sundri (***Heritiera fomes***) and Gewa (***Excoecaria agallocha***) are the two most important tree species although others are harvested in limited quantities.

The FAO project team of BGD/84/056 remeasured a number of Permanent Sample Plots that had originally been measured as part of the ODA survey (Chaffey et al 1985) and approximately 7 year increment information was available. Trees had been measured for diameter breast height over bark in 1986/87 and again in 1994/95. Tree heights had been measured on all trees in 1994/95 but tree heights were measured for only a sample of trees at earlier measurement periods. Tree volume equations had been reported in the ODA report but there have been arguments about their utility. The project needed unbiased equations so as to be able to use the remeasured PSP data to provide predictions of tree and stand volumes. This then was the focus for this work.

The form of Sundri trees is extremely variable, with pronounced and variable buttressing, and cankers and swellings occur on almost all trees. Tree measurement is difficult and time consuming. Experienced, trained crews were not available for the field work required to collect a good basic pool of tree volume measurement data.

PAST TREE VOLUME ESTIMATION

The earliest Sundri tree volume predictors that could be discovered are the tables presented by Suri (1928). The tables presented by Curtis (1933) are slightly different as Curtis argued that the Suri tables were based on data collected from unrepresentative sites, and that the tables were not appropriate for Working Plan preparation.

The Forestal survey (1960) seem to have used Curtis. For the ODA report the project team (Chaffey et al 1985) measured felled trees for some species, including Sundri, and developed some equations. They had insufficient time to collect data for all the other species and develop equations for them, so for these species it appears that they developed equations by putting logarithmic transformed linear regression models through the Curtis tables to provide equations that they could incorporate in their planning.

For Sundri 3 equations are presented in the ODA report, based on height class, to predict under bark tree volumes (m^3) from tree diameter (cm).

Height Class 1, trees >= 15.2 m.

$$\log(Volume) = 1.51076 - 65.9963 * D$$

Height Class 2, trees < 15.2 m, >= 10.7 m.

$$\log(Volume) = 10.2821 * \log(D) - 0.37283 * D - 25.1612$$

restricted so that for D>28 volume = 0.263

Height Class 3, trees < 10.7 m.

$$\log(Volume) = 12.2165 * \log(D) - 0.5125 * D - 28.3046$$

restricted so that for D>24 volume = 0.169

The structural form seems quite inappropriate as the model implies that trees in height class 2 that are greater than 28 cm all have the same volume regardless of tree diameter, and similarly for height class 3 trees greater than 24 cm. These limits would seem to be well within the expected diameter range for Sundri on those sites.

Their use of logarithmic transformations introduces a bias when the linear regression parameters are used to predict tree volume although the linear regression itself is unbiased. The report is unclear, but no indications could be found that the logarithmic bias had been removed in their analyses. Past experience with tree volume equation development suggests ignoring this bias is completely untenable.

A more important practical problem is that their appears to be a typing error in the equation parameters for height class 1, as volume decreases with increasing tree diameter, and is almost zero for all tree diameters from 10 cm upwards. The equation cannot be used as published.

It was decided that the ODA equations could not reasonably be used as presented, and that new equations should be prepared. At the very least it was considered necessary to fell some sample trees and measure them, so that a more objective assessment could be made of the equations from the ODA survey, and decisions taken about which equations to use in processing the Permanent Sample Plot data which would provide resource estimates and assist Forest Department planning. This project required the input of all three authors to make the task succeed and each had their own area of responsibility in ensuring success.

DATA COLLECTION AND SUMMARY

Plots were subjectively sited in a range of Sundri forest types. Although it had been originally hoped to measure more sites, restrictions on field crews, and the availability of other resources, limited the analysis to 6 sites. On each site a 200x100 m plot was established with subplots of 25x25 m established at each corner and half way down each side. There were thus 6 subplots established. The species and diameter (dbhob) were recorded for all trees greater than 2.5 cm diameter were recorded on each subplot. Approximately 5 sample trees were then selected randomly to cover the range of tree diameters, and these were felled and measured. There were approximately 30 trees per plot, a total of 164.

The measurement of these trees was carried out under the supervision of Dr A.Karim. Because all staff were inexperienced, the measurements were not as precise as would have been desirable, but any errors should just be reflected in an increased error term in the analyses and there was no evidence during a limited field inspection by the senior author that any measurements were biased.

The data were then entered into the data base developed by Mr B.C.Sarker and some simple validation checks carried out. Trees with errors were then checked and if possible corrected. A minimal number of 5 trees were rejected because measurement differences could not be reconciled. Tree volumes were then calculated from stump to bole height over bark by summing sections using average cross sectional diameter multiplied by section length to calculate section volume.

Under bark equations should also be developed but in the haste to get at least some equations prepared for immediate project use, this analysis was restricted to over bark equations alone.

The available data are summarised graphically in Figure 1. The first graph shows overbark tree volume plotted against tree diameter. The second shows tree height against tree diameter.

Both graphs show the classic form. It had been expected that the tree volume graph might indicate an asymptotic value for large diameter trees, but such is certainly not the case for this data set.

ANALYSIS

Two separate sets of analyses were carried out, one using tree diameter alone to predict total stem volume over bark, and the other using tree diameter and tree height as the independent variables in the prediction equations.

Predicting volume from diameter alone

Inspection of the data and preliminary analysis showed the distribution of the error about the expected prediction lines to be heteroscedastic. There are two commonly used methods for solving this statistical problem:

- to use logarithmic transformations, and,
- to use a weighted linear regression analysis.

The preferred method is to use a weighting function as the logarithmic transformation provides a biased tree volume prediction model even though the regression analysis is in itself unbiased. The ODA study used logarithmic transformations.

When the ODA model form was run the linear term in (D) was not significant which was quite surprising as it had been included in almost all the ODA equations. The equations were as follows with the standard error of the parameter estimates being shown directly underneath the parameter.

$$\log(V) = \underset{(0.257)}{-8.566} + \underset{(0.154)}{2.283} * \log(D) - \underset{(0.00964)}{0.00315}\, D$$

$$\log(V) = \underset{(0.100)}{-8.643} + \underset{(0.035)}{2.332} * \log(D)$$

The plot of the residuals still showed heterogeneous variance and the model bias was considered unacceptable. The ODA equations for height classes 2 and 3 predict constant tree volume for all trees greater than 28 and 24 cm respectively in diameter, and this can be seen to be somewhat problematic when Figure 1 is inspected. This shows that volume continues to increase as tree diameter increases up to at least 30-35 cm, and the suggestion is that any asymptote is much higher.

When tree volume was used as the dependent variable the regressions were weighted by $(1/(D^2)^2)$ which is equivalent to weighting the data by $(1/D^2)$. The plot of residuals against tree diameter confirmed that all regressions were satisfactory and that the error term could be considered homogeneous.

The linear and quadratic term models are detailed below. The addition of a cubic term was not significant when added to the quadratic model. This was not surprising given the spread of the data as shown in Figure 1.

$$V = \underset{(0.00365)}{-0.06507} + \underset{(0.00045)}{0.01200} * D$$

$$V = \underset{(0.00469)}{0.01394} - \underset{(0.000911)}{0.004385} * D + \underset{(0.0000362)}{0.0006779} * D^2$$

Experience suggests that a simple power function may be better than the polynomial model form, and it also has the advantage of being readily constrained to pass through the origin. When fitted, the residual sum squares was less than for the quadratic model with one more parameter. The power function is more efficient, simpler, of more acceptable form, and was preferred.

$$V = \underset{(0.00001907)}{0.00017809} * (D ** \underset{(0.0364)}{2.3358})$$

If tree heights are not available then this model can be used to predict Sundri tree volumes.

Predicting volume from diameter and height

For these models the linear regressions were weighted by $(1/(D^2H)^2)$ which is equivalent to weighting the data by $(1/D^2H)$. This weighting factor is commonly used, for example in Burma (Shwe Kyaw et al (1990) and in Australia (reported in Leech 1993).

The simple so-called combined variable equation proved to be an efficient estimator of tree volume. The residuals showed no obvious trend with tree diameter and the model seemed sensible.

$$V = \underset{(0.000508)}{0.001916} + \underset{(0.00000059)}{0.00003421} * D^2H$$

$$V = \underset{(0.000818)}{0.000352} - \underset{(0.00000251)}{0.00002759} * D^2H + \underset{(0.0000350)}{0.0000847} * D^2$$

$$V = \underset{(0.002647}{0.003559} - \underset{(0.00000075)}{0.00003450} * D^2H - \underset{(0.0003334)}{0.0002110} * H$$

The height term (H) was not significant when added to the simple two parameter model, and this model was therefore rejected. The addition of (D^2) was significant when added to the model and is preferred.

Because the data had been obtained from 6 different sites, covering site class I, II and III Sundri, and because the ODA and also Curtis had developed separate models for each site class, an analysis was carried out to determine whether or not the regressions should be estimated separately for each tree measurement site, or whether the data could be pooled across all sites.

Dummy variables were added to the simple combined variable equation, with three alternative models being run:

- allowing the constant to vary between each of the six sites,
- allowing the coefficient to vary between sites, and,
- allowing both coefficient and constant to vary between sites.

Inspection of the various parameter estimates showed that there were no significant differences between sites for any of the analyses and that was quite surprising. The data could all be pooled and a single regression model obtained with just three parameters.

Because the power function had proved to be the better prediction model not using tree height the extended power function was also fitted. When fitted, the residual sum squares was less than for the extended combined variable equation also with three parameters. The power for height was significantly different from 1.0 although that for diameter was not significantly different from 2.0 which was a little surprising. It did not seem sensible to constrain the power for diameter and not for height. This model is more efficient than the alternatives and is the preferred model including tree diameter and tree height.

$$V = \underset{(0.000000824)}{0.000006083} * (D ** \underset{(0.0462)}{1.9631}) * (H ** \underset{(0.0863)}{0.8270})$$

If tree heights are available then this model can be used to predict Sundri tree volumes.

FUTURE WORK

The analysis presented shows that it is possible to develop tree volume equations that are superior to any others that could be found for Sundri in the Sundarbans in Bangladesh. These equations should be extended to predict under bark volume as well as over bark volume, and equations should also be developed to predict total stem volume to various top diameter or height limits.

Branch volumes and weight information were available but there was insufficient time to carry out any analysis.

Given the difficulties encountered with the ODA equations it is recommended that equations should be developed for species other than Sundri. One problem in developing tree volume equations in mixed species forest is to determine how the equations for different species should be aggregated. This is less of a problem in the Sundarbans where there are limited species. but the statistical problems do occur. Complex methods such as those used by Leech. Correll and Aung Kyaw Myint (1991) in Myanmar would work, but are probably unnecessary and the simple use of dummy variables would enable all inter species comparisons to be made.

There are indications from the ODA equations that it may be quite possible to aggregate species into combined equations, but this should await extra data and new analyses.

SUMMARY

The study developed tree volume equations for Sundri that are considered satisfactory for use in the initial stages of the calculation of the resource estimates that are necessary for planning the management of the Sundarbans Reserved Forest. The study indicates that past analyses are problematic and that data should now be collected, and equations developed, for all tree species. However it is extremely unlikely that any such work can be carried out during this project.

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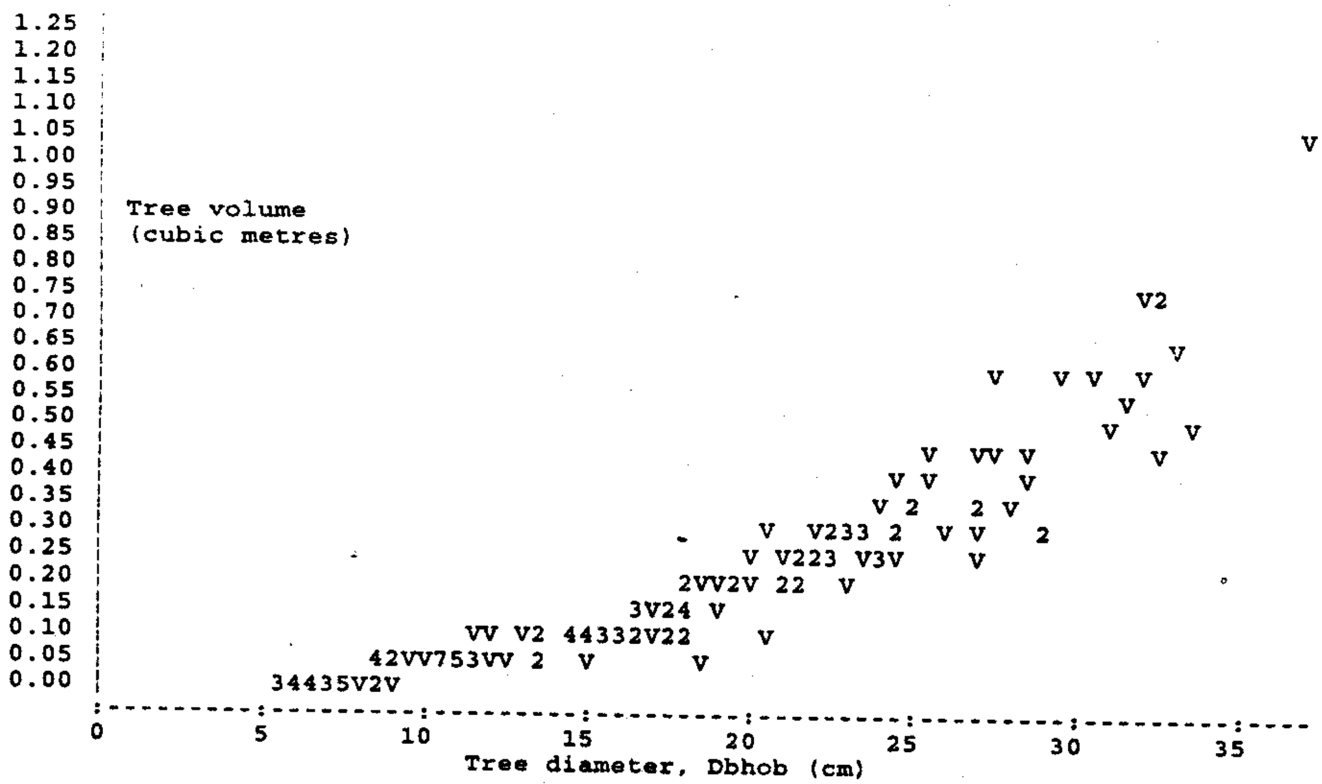
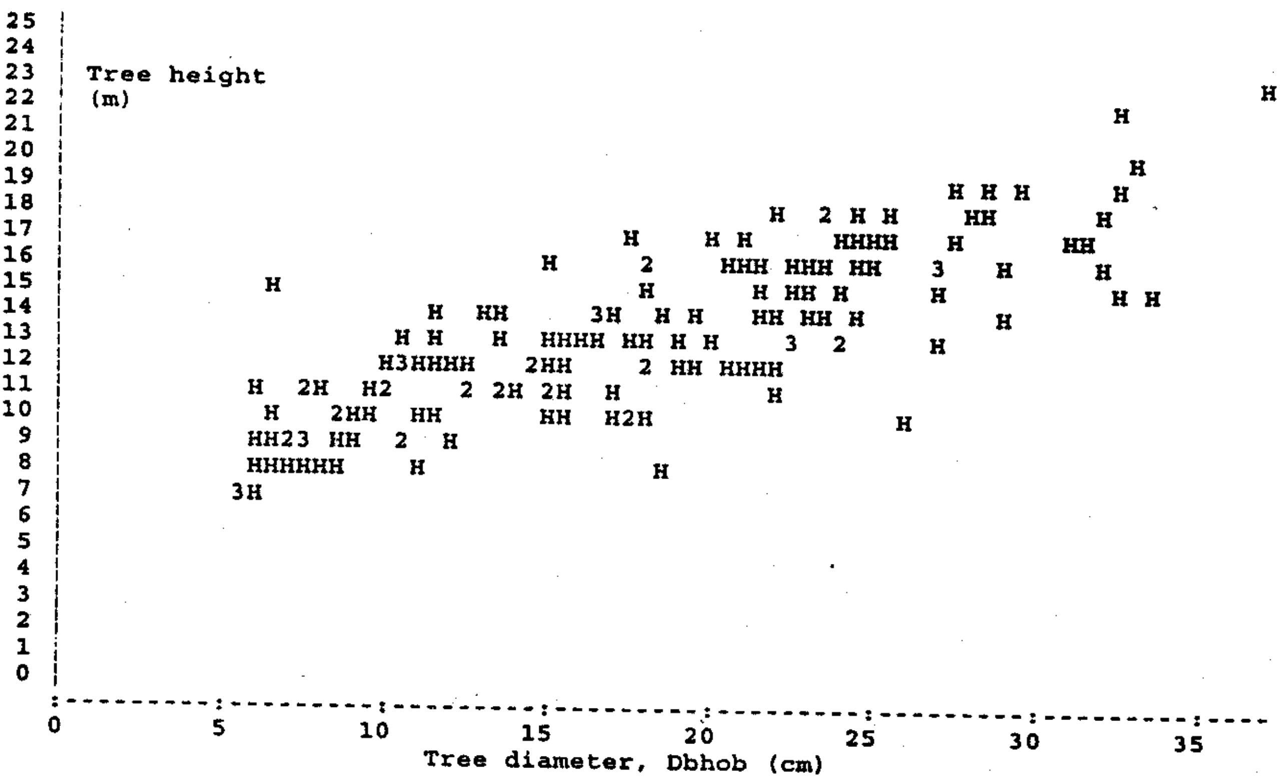
Figure 1


Tree volume
(cubic metres)
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
30
35
Tree diameter, Dbhob (cm)


Tree height
(m)
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
5
10
15
20
25
30
35
Tree diameter, Dbhob (cm)

APPENDIX 4: Gewa Tree Volume Equations

There was insufficient time during the second mission to develop tree volume equations for Gewa.
Between the second and third missions, and at the request of Dr A.Karim, Mrs Nazma Ahmed had developed equations to predict tree volume from stump to two arbitrary top diameter limits, 5 cm and 10 cm. At the start of the third mission these were reviewed. Investigation showed problems with these equations.

- The equations had been developed using OLS (Ordinary Least Squares) and not WLS (Weighted Least Squares) using the weighting factors defined in Appendix 3.
- The best models presented were the two second order polynomials which provided inconsistent estimates for some tree diameters, with predicted volume to 10 cm being greater than predicted volume to 5 cm top diameter.

These models could not be used in practice.

Further, the revised Sundri analysis showed, as expected, that the power function models are better than simple polynomials and that they are more efficient and have fewer parameters.

Data

There were 61 felled Gewa trees with measurements that could be used for the analysis. These were briefly reviewed to determine suitability, this after measurements had been checked by Dr A.Karim. One tree was rejected because there were no measurements between an underbark diameter of 11.7 cm and the tip, presumably because the crown had smashed on felling. This would give peculiar estimates of volume to 5 cm top diameter. The largest felled tree was considerably larger than the next largest and was ignored, not because the tree was inadequately measured, but because it was thought that the tree would have exerted too great a leverage on the regression models even considering the weighting factors used.

There were therefore 59 trees available for the analysis.

The data were extracted from the IDB. Apart from tree diameter and tree height three volume estimates were extracted.

V00 Volume between stump and the tip.
V05 Volume between stump and 5 cm top diameter underbark.
V10 Volume between stump and 10 cm top diameter underbark.

Volumes were calculated as overbark volumes for this analysis. Of the 59 trees 37 had volume to 10 cm and had a tree diameter greater than 10.0 cm. This assumption of a minimum pulp length of about 1.1-1.3 m seemed appropriate.

Methodology

The approach that was really required was ideally a coherent multi-variate regression approach, but given there were only 59 observations, the quality of the felled measurements, and lack of time, this seemed to be inappropriate.

The alternative approach was to develop a model to predict the merchantable volume from stump to the tip of the tree (V00) from tree diameter and possibly tree height and then to develop separate models to predict the volume between the tip and the two utilisation limits. This was thought to be a better approach as it would assist ensuring that the model development provided consistent and coherent models.

Model Development

When linear polynomial models were evaluated the cubic term was found to be not significant, and for the quadratic model neither the constant nor the linear term was significant. The best model was the simple single parameter equation, a power function with the power of 2.0.

$$\begin{array}{llll} V00 = & -0.02924 & + 0.007541\ D & \\ & (0.00306) & (0.000433) & \end{array}$$

$$\begin{array}{llll} V00 = & 0.000503 & - 0.000029\ D & + 0.0004189\ D^2 \\ & (0.006010) & (0.001436) & (0.0000771) \end{array}$$

$$\begin{array}{ll} V00 = & 0.0004218 * D^2 \\ & (0.0000120) \end{array}$$

When the nonlinear power function was evaluated the power was found to be very close to 2.0 and not significantly different. This suggested that the simple linear form equation was quite satisfactory.

The dependent variable was changed to V05 and V10 and the power function evaluated.

$$\begin{array}{lll} V00 = & 0.0004139 * & (D ** 2.0100) \\ & (0.0000663) & (0.0653) \end{array}$$

$$\begin{array}{lll} V05 = & 0.0002630 * & (D ** 2.1650) \\ & (0.0000487) & (0.0736) \end{array}$$

$$\begin{array}{lll} V10 = & 0.0000198 * & (D ** 2.9621) \\ & (0.0000078) & (0.1372) \end{array}$$

For the V00, the volume between stump and tip, the power is not significantly different from 2.0 which means that the simple linear model with the quadratic term is the best model. The progression of the powers with the power increasing as the top diameter limit increases is interesting, sensible, and as expected. The models imply that for some large diameter the graphs would cross and that the predicted volume to 10 cm top diameter would be larger than that to 5 cm which in turn would be larger than volume to the tip. Thus the power functions cannot be used to predict V05 and V10.

The actual volume between the tip and 5 cm and between the tip and 10 cm were then used as the dependent variables in extending the analyses. A number of simple models were fitted.

$$\begin{array}{lll} V00\text{-}V05 = & 0.003017 & - 0.00005427\ D \\ & (0.000310) & (0.00002410) \end{array}$$

$$\begin{array}{llll} V00\text{-}V05 = & 0.004106 & - 0.0002334\ D & * 0.000006255 * D^2 \\ & (0.000677) & (0.0001023) & (0.000003465) \end{array}$$

$$\begin{array}{lll} V00\text{-}V05 = & 0.001502 & + 0.008738\ /\ D \\ & (0.000303) & (0.002801) \end{array}$$

$$\begin{array}{lll} V00\text{-}V10 = & 0.03438 & - 0.0009523\ D \\ & (0.00388) & (0.0002552) \end{array}$$

```
V00-V10 = 0.05802   - 0.003951    D * 0.00008684  * D²
          (0.01337)  (0.001647)     (0.00004715)

V00-V10 = 0.002032 + 0.2506    / D
          (0.004488) (0 0592)
```

The linear model is unsatisfactory as the expected value of the dependent variable becomes negative at some large diameter. A cubic term was not significant when added to the quadratic model. The reciprocal model with two parameters is more efficient than the quadratic model. The model structure makes sense as it implies that as tree diameter increases the volume at the tip decreases but only approaches zero, never reaching it.

The parameters for the (V00-V10) model are both greater than the equivalent parameters for the (V00-V05) model which ensures that the estimated volume to 10 cm will always be less than the estimated volume to 5 cm.

These reciprocal model are therefore the preferred models.

Preferred model

The preferred prediction equations for Gewa are therefore a combination of the equations below.

```
V00 =   0.0004218 * D**2

V00-V05 = 0.001502 + 0.008738 / D

V00-V10 = 0.002032 + 0.2506   / D
```

These can be reformatted to provide predictors of over bark volume to 5 cm and 10 cm top diameter.

```
V05 = 0.0004218 * D**2 - 0.001502 - 0.008738 / D          if D>= 5.0
V05 = 0.0                                                    D<  5.0

V10 = 0.0004218 * D**2 - 0.002032 - 0.2506   / D          if D>=10.0
V10 = 0.0                                                    D< 10.0
```

These equations can be coded and used in the prediction procedures of the IDB to prepare outputs for the IRMP.

Summary

The analysis showed that simple models can be prepared to predict Gewa utilisable volume to both 5 cm and 10 cm top diameter.

The computer files for these analyses have been left with Mr B.C.Sarker.

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