the Mpingo Conservation Project

Rapid Stocks Assessment of Mpingo & Other Timber Species for Kilwa District

First Full Draft

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A final draft will follow incorporating the further work set out in the conclusions at the end of this report.

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Executive Summary

In common with other parts of the developing world, up-to-date data on timber tree stocks in southern Tanzania is not available. Management of sustainable felling depends on accurate assessment of standing stocks, but inventories require a large investment of time and resources which economically straitened governments rarely have. Harvesting quotas therefore tend to be primarily demand driven, and hence potentially unsustainable.

Previous work by the Mpingo Conservation Project had highlighted the lack of current data on stocks of mpingo *Dalbergia melanoxylon*. A stocks assessment was thus a major objective of the work carried out under the 2004 award won by the Project in the BP Conservation Programme. Resources available for the assessment were nonetheless constrained, and so a rapid assessment methodology which minimised time and costs was adopted. An additional objective therefore came to be the evaluation of the rapid survey techniques, and their potential applicability elsewhere.

The assessment covered Kilwa District, part of Lindi region in southern Tanzania, and where the Project is based. Kilwa District itself covers over 13,000km², most of which is miombo woodland of various types, but also includes significant patches of East African Coastal Forest. Forest cover is still relatively high, and only in the northern part of the district are large swathes cleared for agriculture. The assessment covered eight species other than mpingo: *Swartzia madagascariensis*, *Pterocarpus spp.*, *Milicia excelsa*, *Millettia stuhlmanii*, *Khaya anthotheca*, *Combretum imberbe*, *Afzelia quanzensis* and *Bombax rhodognaphalon*, although insufficient data was collected on some to compute figures for total stocks.

A total of 28 rapid transects were walked between August and November 2004, which, put together, extended approximately 160km. Transects were sub-divided into segments according to vegetation cover, which was then classified in relation to topographic maps derived from aerial photography dating back to 1965-6, and digital land cover data obtained from LandSat images taken in 1995. Surveyors estimated the diameter and straight length of stem of all individuals of the 9 target species whose DBH was at least 20cm (for mpingo) and 25cm (for all other species), and which the surveyors judged to lie within 10m of the transect line.

Survey data was then adjusted according to surveyor performance on a dedicated calibration course. Adjustments had to be made to take account of subjective perception of transect width and error in estimating stem diameter and straight length.

In assessing harvestability a number of different harvesting models were considered for each species. Model parameters were defined on a species-by-species basis for the following scenarios: *Market Preference*, *Legally Harvestable Now*, *Potentially Legally Harvestable Later*, *Illegally Cuttable Now* and *Usable Locally*. As only estimates were available for the physical dimensions of each recorded tree a probabilistic approach had to be adopted when computing harvestability under the different models. Similarly the harvestable volume of surveyed trees could only be computed as an expected result. The accuracy of these technique was calibrated using the same calibration data, and adjusted appropriately. Confidence limits were determined for each step of the calculation, and combined to produce confidence intervals on the final figures for district-wide stocks of each species.

Sample sizes varied from only 6 observed individuals for *Swartzia madagascariensis* and *Khaya anthotheca*, which were deemed data-deficient, up to 608 for mpingo. Total derived stocks for mpingo are presented in Table 1. The confidence level on the number of harvestable trees is 80%, except for the dummy *All Trees* harvesting model for which the confidence level is 85%. The confidence level on the figures for harvestable volume is 85% in all cases. We estimate the total population of trees (with DBH $\geq$ 20cm) to be somewhere between one and two million trees, but the number of legally harvestable trees is roughly half that. The number of trees with dimensions at market preference is half that still, although there is only a one-third further reduction in harvestable volume.

Model	Num Harvestable Trees (x 1,000)		Harvestable Volume (x 1,000 m^3)	
Market Preference	350	(234 - 611)	171	(121 - 253)
Legally Harvestable Now	771	(516 - 1,116)	257	(205 - 346)
Potentially Legally Harvestable Later	855	(598 - 1,194)	252	(215 - 309)
Illegally Cuttable Now	1,006	(678 - 1,419)	281	(237 - 357)
Usable Locally	1,010	(679 - 1,422)	281	(237 - 358)
All	1,518	(1,066 - 2,096)	296	(248 - 374)

Table 1. Total expected number of harvestable trees and total expected harvestable volume of mpingo in Kilwa District harvestable under different models, with confidence intervals (see note above).

Total stocks of other surveyed species under the *Legally Harvestable Now* model are set out in Table 2. The confidence intervals are much wider in all cases except for *Pterocarpus spp.*

Species	Num Harvestable Trees (x 1,000)		Harvestable Volume (x 1,000 m^3)	
Pterocarpus spp.	151	(83 - 280)	197	(109 - 415)
Milicia excelsa	16	(4 - 68)	70	(42 - 123)
Millettia stuhlmanii	11	(3 - 42)	14	(9 - 19)
Combretum imberbe	118	(22 - 466)	61	(26 - 130)
Afzelia quanzensis	27	(12 - 78)	45	(30 - 70)
Bombax rhodognaphalon	55	(22 - 146)	319	(214 - 440)

Table 2. Total expected number of legally harvestable trees and total expected harvestable volume in Kilwa District by species, with confidence intervals (see note above).

However, various doubts have been raised about the accuracy of these figures, which are generally on the high side, and more analysis is required to verify them. Particular attention needs to be paid to the problems of land use cover data, which were neither recent nor always reflective of the ecological characteristics of the surveyed species.

Nonetheless we consider the study a success, and the methods employed would be appropriate for use in woodlands elsewhere, and in circumstances where limited financial resources are available for the task. The study demonstrated a factor 5 cost-efficiency gain (in terms of the area covered for each unit investment of manpower) over a similar survey commissioned by the Tanzanian government which used methods based on traditional sample plots.

Acknowledgements

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Contents

Introduction

"The overall forest management [in Tanzania] has for years been based on outdated and unreliable data and information" (MNRT 2001)

In common with other parts of Tanzania, up-to-date data on timber tree stocks in Kilwa District is not available, and this represents a serious hindrance to effective management of forest resources in the district (Milledge & Kaale 2005). There was an inventory in 1970, and another in the 1990s for which no figures were released to the district authorities (M Mfangavo *pers. comm.*). Harvesting quotas therefore tend to be primarily demand driven, and hence potentially unsustainable. Since the 1990s District logging licence records show that the volume of timber felled has increased, as has the diversity of species for which licences have been obtained. In order to determine what off-take can be sustainably supported, and how long current logging pressure can be sustained, it is essential to know how much timber there is in the district, both of mpingo and other valuable hardwood species.

Previous work by the Mpingo Conservation Project (MCP) had given detailed data about mpingo stocks and habitat correlates in relatively small areas, however attempts to extrapolate to wider areas had introduced too many variables (Ball 2004). A major objective of the MCP under BP Conservation Programme funding was to estimate stocks across the whole of Kilwa District. By relating located timber stocks to other factors, such as habitat type, determined from pre-existing GIS, this information can be used to help determine stocks levels elsewhere in an efficient manner.

However inventories are time consuming and expensive. The Tanzanian government agency, the Forestry and Beekeeping division commissioned a set of inventories in 2005 which budgeted 788 man days in the field divided between 11 districts, and that ignores preparation and travel time, and assumed an optimistic 4-6 sample plots could be completed per day by each team (Malimbwi *et al.* 2005). Even then, only partial inventories were conducted; in Kilwa a total of 24 forest blocks were visited, although 3 were in strictly protected reserves where no harvesting is permitted. The 21 production forest blocks covered a total of 3,800km² in a district of over 13,000km².

The MCP set out to survey stocks across the entirety of Kilwa District, but with the minimum use of manpower in order to control costs. This report evaluates both the results that were obtained, and the methods used to derive them.

Context of this study

Kilwa District is the most northerly district in the Lindi Region of southern Tanzania. It covers an area of over 13,000km². To the north is Rufiji District in Pwani Region, to the east the Indian Ocean, to the south Lindi Rural and Ruangwa Districts, and to the west is the Selous Game Reserve.

Most of the District is well-drained sedimentary sandstone with low fertility and low moisture-holding capacity. Three of the four main rivers of the Lindi Region, namely the Matandu, Mbwemkuru and Mavuji Rivers, run eastwards through the District into the Indian Ocean.

Kilwa District is one of the hottest in the country because it is coastal and low-lying. Temperatures along this coastal strip are high, averaging 25°C with little seasonal variation (Burgess *et al.* 1998). There are two rainy seasons. Typically the 'short rains' (*vuli*) are light rains falling from November to January. After a drier period around February, there are the 'long rains', (*masika*), which are heavier and usual last from March to May. Relative humidity tracks rainfall, peaking in March-April (UNPF 1997). Mean annual rainfall of just over 1000mm (MCP 2006), puts it just inside Chidumayo's wet miombo vegetation category (Chidumayo 1997).

Land cover

At a macro scale, miombo vegetation is considered to be very uniform. On a smaller scale, as a result of topography and soil, it includes areas of grassland, thicket, forest and other woodland (Chidumayo 1997). Kilwa District is on the eastern edge of the central African miombo belt, and the vegetation is very heterogeneous, with a variety of vegetation types associated with the miombo region, and other types of vegetation associated with the coastal strip of East Africa (Ornis Consult 2002).

Along the low lying coastal strip of the District, the vegetation is predominantly deciduous scrub with scattered trees. There are substantial areas of seasonally flooded sandy soil, and much scattered cropland.

Running down the centre of District are dissected plateaux of slightly higher lying land (100m asl) with fragments of the globally important biodiversity hotspot East African Coastal Forest (Burgess *et al.* 1998). Most of the miombo lies to the west of the coastal forest, and is interspersed with bushland and seasonally-flooded open areas of grassland.

In the far west of the District, bordering the Selous Game Reserve, the large mammal population is high. Their grazing and browsing have a substantial impact on the vegetation, which is generally short and open. Although the dominant trees here are mostly typical miombo species such as *Brachystegia longifolia* and *Diplorhynchus condylocarpon* they are unable to grow to their full stature by very high browsing pressure, and being weakened by frequent fires set by villagers and hunting block owners.

Historical Forest Exploitation

Kilwa District has been settled for over a thousand years. For most of that time the main settlement was on the island of Kilwa Kisiwani. Although there was agriculture on the mainland and a trade route heading inland though, the population is believed to have had only a small impact on woodland cover (P. Blanchard *pers. comm.*). Most settlement, and hence farming, was on the coastal strip whose shallow seasonally inundated soil does not support many timber species. During this time the majority of timber used is likely to have been mangrove, used in house construction; *Pterocarpus*, used for traditional boat building which continues to this day and *Afzelia quanzensis* which was used for making doors.

In the early and mid-twentieth century the colonial rulers gazetted Forest Reserves to safeguard their supplies of timber against uncontrolled use and clearance. Reserves were also established for protection of catchments and these were later recognised as being important for biodiversity protection. All 11 of the Forest Reserves in the District were initially established during colonial times, and all are under central government control. According to the District Forestry Office they cover a total area of 2,071km².

Current Forest Exploitation

The District's population has remained relatively stable partly because of out-migration from the District, as young people have sought education and economic opportunities elsewhere (UNPF 1997). Currently there are about 175,000 people living in Kilwa District[1], which is a density of 12.6 people per km². The average person in Kilwa District lives in a house built in the traditional way from forest products such as poles, bamboo and mud, with a roof made of grass (Central Census Office 2004).

Until May 2000 the District was inaccessible, being linked to Dar es Salaam, by a single ferry across the Rufiji River. The construction of the Mkapa Bridge across the Rufiji was an essential investment facilitating much-needed development in the impoverished area to the south. Movement of people and goods is possible, but difficult, even in rainy months. It has become cheaper to send local goods to market in Dar es Salaam, and transport costs to bring manufactured goods from outside the area in, for sale, have decreased. New businesses are opening, particularly in Kilwa Masoko, and many businesses based outside the District have also benefited.

However, the bridge has greatly increased pressure on forest resources such as timber and charcoal (Milledge & Elibariki 2005). Villagers living along the Dar-Mtwara (B2) road produce charcoal and take advantage of passing goods vehicles to sell it to urban residents. With the exception of Kilwa Masoko, Kilwa Kivinje, Nangurukuru, and some of the larger villages along this road, where food vendors and wealthier residents buy charcoal, there is sufficient fuel wood available that women and children can readily meet household needs from the surrounding land.

[1] Figure based on 2002 census (Central Census Office 2004).

Field Methods

Kilwa District covers over 13,000km², and so a rapid, efficient methodology was required in order to estimate timber stocks district-wide. The methods used were based on that trialled by (by Ball 2003) on *Tabebuia spp.* in Brazil which trades accuracy for speed. The resulting analysis cannot be said to be very accurate for sub-divisions of the overall survey area, but yields results for the whole study area without requiring a massive investment in field time.

Transect walks have a substantial efficiency advantage over discrete sample plots since there is no separate travelling time; staff are surveying the entire time from the start to end of the transect. This advantage is extended if transects start and end at roads rather than randomly located points in the bush, a strategy which also makes logistics easier. Instead, therefore, of using random sampling, the field team deliberately selected transects which crossed an area of bush from one road or track to another, aiming to distribute these transect walks roughly evenly across the district. Transects were planned using an old road map of the District based on early 1960s data[2], and the planners had at best a hazy idea of the likely habitat between the two points, so reducing bias.

In total 28 straight-line transects were walked between 31st August and 17th November 2004, covering a total length of approximately 160km. Each transect was completed in a single day. Their locations are shown in Figure 1. Note that some transects appear to extend outside the district. This in fact is an error in depicting the district borders in the digital maps which are obtainable. While the eastern boundary (the sea) and the southern boundary (Mbwemkuru River) are fixed and readily deducible from satellite images, the northern and western boundaries are approximations only based on limited data.[3] All transects definitely took place within the district boundaries as verified by District staff and local villagers.

A GPS waypoint reading was taken at the start and end of each transect, and at each point the field team observed the vegetation type to change. These waypoints thus divide the transects into one or more Transect Segments, each with its own recorded habitat description, and allow calculation of the straight line length of each segment. Habitat descriptions were left up to the field team to record freehand, resulting in over 300 different descriptions recorded in 390 transect segments. Descriptions were later classified according to analytical requirements.

[2] Although much as changed since then, for example settlements and whether roads are passable by vehicle, the roads have generally not shifted their routes significantly, and reliable planning is possible.

[3] Various paper maps of the District that we have seen indicate the western boundary to be in three different places.

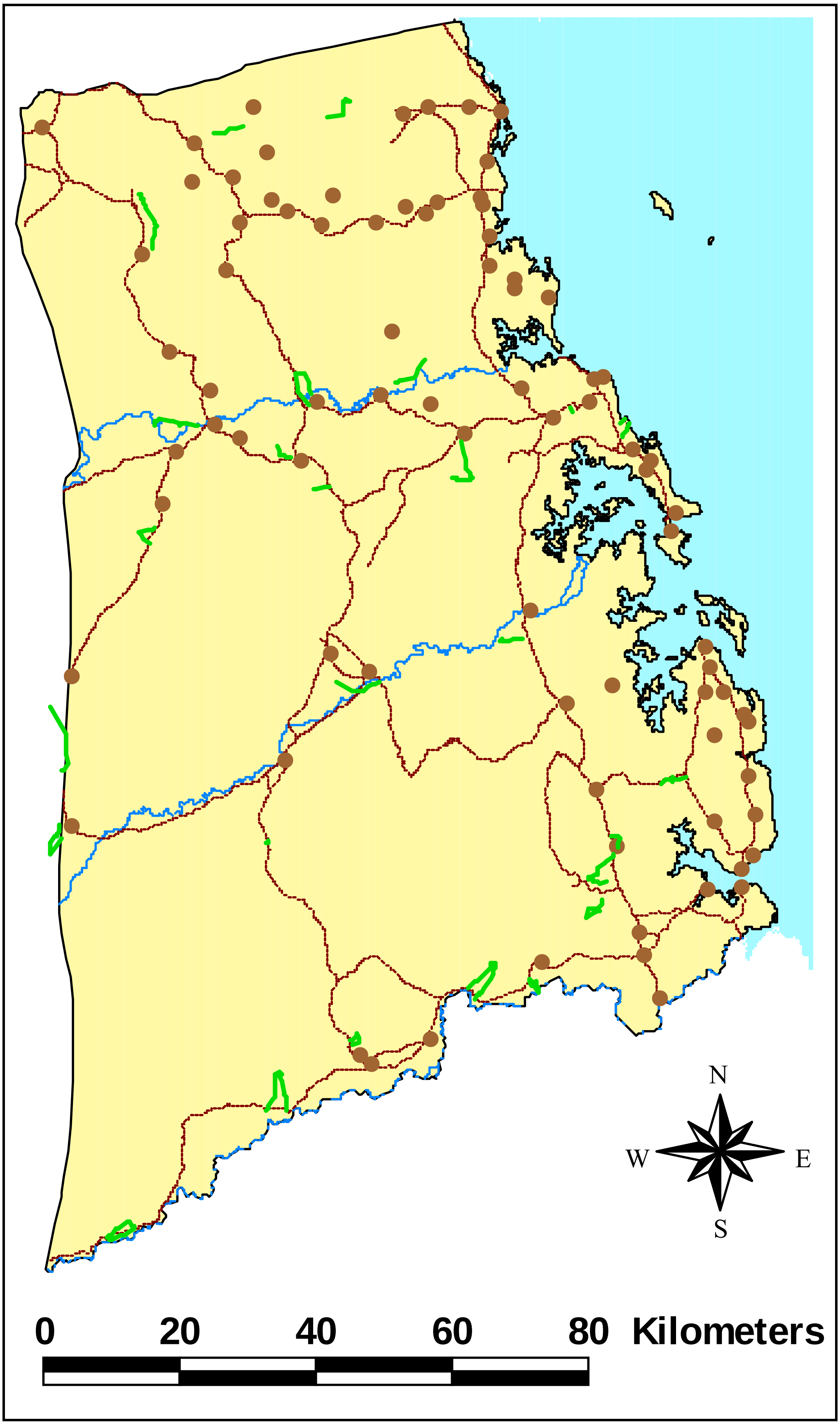

Figure 1. Location of transects walked (in green) with main roads and rivers of Kilwa district. Northern and western boundaries of district approximate only.

Nine species of timber tree were identified from recent licence data as the prime targets of commercial loggers operating in the District[4]. Individuals of these important species, listed in Table 3, were recorded when encountered on a transect segment.

Vernacular name	Latin Name	Min. harvestable diameter (cm)	Timber class
Mpingo	*Dalbergia melanoxylon*	24	1
Msekeseke	*Swartzia madagascariensis*	24	1
Mninga (maji) *	*Pterocarpus spp.**	45	1
Mvule	*Milicia excelsa*	55	1
Mpangapanga	*Millettia stuhlmanii*	*none specified*	1
Mkangazi	*Khaya anthotheca*	55	1
Mhama	*Combretum imberbe*	24	2
Mkongo	*Afzelia quanzensis*	55	2
Msufi pori	*Bombax rhodognaphalon*	55	4

Table 3. Surveyed species; harvestable diameter and timber class from GoT (2004).
*** Includes both *Pterocarpus angolensis* (mninga) and *Pterocarpus holtzii* (mninga maji).[5]**

We recorded all timber trees seen within 10m of the transect line, and with an estimated DBH of at least 10cm for mpingo (*Dalbergia melanoxylon*), and at least 25cm for other species. However, in most of the analysis mpingo trees estimated to have a DBH of 10cm or 15cm are ignored. The 10m transect width was the maximum which allowed easy spotting of timber trees down to 10cm DBH in all vegetation types.

Most large timber trees are relatively straight forward to survey, but mpingo is frequently multi-stemmed, and its convoluted growth patterns often mean that the section of the stem emerging from the ground would not be the target of loggers, but some section higher up. Thus for each qualifying timber tree we noted the DBH of each stem, and the diameter (whether at breast height or elsewhere) and the (potentially harvestable) Straight Length (SL)[6] of each Stem Section which might interest loggers. From the two recorded dimensions we can calculate a resulting Straight Volume (SV) for each stem section. Where mpingo stems over 10cm DBH were unsuitable for harvesting we recorded a reason why they could not be harvested, i.e. because they were crooked, branched, partially dead or a stump.

In order to maximise surveying speed all measurements were estimated by eye rather than actually measured. Three precautions were taken to minimise estimation errors:

1. All members of the field team underwent training and conducted trial transects, under the guidance of logging supervisors before commencing the work.
2. Additionally all surveyors completed a calibration course of 170 trees whose actual measurements were known. The results were used to adjust actual estimates.
3. Diameter estimates were recorded to the nearest 5cm and straight lengths to the nearest 50cm, which is quicker and easier for a trained surveyor than demanding estimates to the nearest centimetre.

The intent was to stop at each recorded tree for as short a time as possible, and not to depart from the transect line unless necessary to gauge harvestability.

[4] The list comprises over 90% of the timber licences awarded over the past 5 years, and include all the species locally harvested that are known to be exported.

[5] The two species have similar timber and are classed together by harvesting regulations, hence their treatment together by this analysis.

[6] This is the same as the Estimated Straight Length (ESL) measure introduced by Gregory *et al.* (1999).

Land Cover Data

1965 Topographic Maps

We used two different sources of land cover (vegetation cover) data. The first is the Series Y742, Edition I-TSD 1:50,000 topographic and land-use maps available from the Ministry of Lands based on aerial photography carried out in 1965-6 by Spartan Air Services of Canada.[7] These remain the only large scale maps easily obtainable for Tanzania. They have not been digitised. Village locations are no longer reliable, having been considerably altered during the Ujamaa programme of villagisation in the 1970s, but most other features are broadly accurate. In a random selection of 44 waypoints, the tree cover recorded by field surveyors was found to be broadly consistent with the vegetation cover depicted on the 1965 maps in 64% of cases.

Vegetation is classified into 12 different types on the 1965 maps, although some of these had negligible appearance in Kilwa District. A crude estimate of total cover for each vegetation type was obtained by counting map squares across all the sheets covering Kilwa District[8]. Table 4 lists the main categories of land cover in the district according to the 1965 maps.

Classification	Total Cover (ha)	Percentage Cover
Forest	142,203	10.7%
Scattered Trees	127,584	9.6%
Scrub	720,318	54.2%
Settlement	46,515	3.5%
Thicket	31,896	2.4%
Water	15,948	1.2%
Woodland	244,536	18.4%
TOTAL	**1,329,000**	**100.0%**

Table 4. Vegetation cover of Kilwa District estimated from 1965 Maps.

1995 Satellite Images

Our second source of land cover data was a series of ArcView GIS shape files generated from composite LandSat TM images with a 30m x 30m resolution taken in 1994-5[9]. The images had already been interpreted into land-use classes and merged by technicians as part of the National Reconnaissance Level Land Use and Natural Resource Mapping Project of 1997. The shape files were merged using ArcView GIS and clipped according to the boundaries of Kilwa District, to produce Figure 2. Table 5 lists the various categories of land cover in the district according to the 1995 LandSat images.

[7] Sheet nos. 239/4, 240/3, 240/4, 255(1-4), 256(1-4, E), 269(1-4), 270(1-4), 271/1, 271/3, 282(1-4), 283/1 and 283/2. 239/3 (Kurgurwe) and 284/1 (Mchinga) were not used; each of these two includes only a tiny corner in Kilwa District.

[8] Except for the above-mentioned two corner sheets.

[9] The exact sheets used were as follows (information courtesy of Simon Mwansasu, IRA, UDSM):

- Kipatimu sheet based on landsat scenes 166/66 (09-06-95) and 167/66 (15-07-95)
- Kilwa sheet based on scenes 165/66 (30-05-94) and 166/66
- Liwale sheet based on scenes 166/66, 166/67, 167/66 (15-07-95) and 167/67 (16-06-95)
- Lindi sheet based on scenes 165/66, 165/67 (30-05-94) and 166/66, 166/67

Super Class	Classification	Total Cover (ha)	Percentage Cover
Bushland	Dense Bushland	639	0.05%
	Bushland with scattered cultivation	109,338	8.44%
	Thicket	299	0.02%
	Thicket with emergent trees	13,414	1.03%
	Bushland with emergent trees	76,543	5.91%
Cultivated Land	Mixed Cultivation	20,935	1.62%
	Cultivation with tree crops	42,976	3.32%
Forest	Mangrove *	4,153	0.32%
	Natural Forest	2,763	0.21%
Grassland	Open Grassland	618	0.05%
	Open Grassland, seasonally inundated	5,176	0.40%
	Bushed Grassland	76,407	5.89%
	Bushed Grassland, seasonally inundated	7,535	0.58%
	Grassland with scattered cultivation	24,923	1.92%
	Wooded Grassland	130,850	10.09%
	Wooded Grassland, seasonally inundated	46,534	3.59%
Open Land	Bare Soil *	210	0.02%
Urban	Urban Areas / Airfields *	157	0.01%
Water	Inland Water / Lake *	238	0.02%
	Swamp / Marsh *	223	0.02%
Woodland	Woodland with scattered cultivation	146,773	11.32%
	Closed Woodland	253,929	19.59%
	Open Woodland	331,587	25.58%
TOTAL		**1,296,220**	**100.00%**

Table 5. Vegetation cover of Kilwa District according to 1995 LandSat images.
*** indicates land covers assumed to have zero stocks of timber species under consideration.**

Not all land cover 1995 LandSat classifications listed were found to be surveyed. Mangroves, open land soil, water and urban areas were not surveyed but were assumed to have zero stocks of the species under consideration. Use is made locally of some mangrove species, for example in house and boat construction, but as the market is different from that for terrestrial timber species, and the field surveying would be difficult, mangrove was excluded from this work.

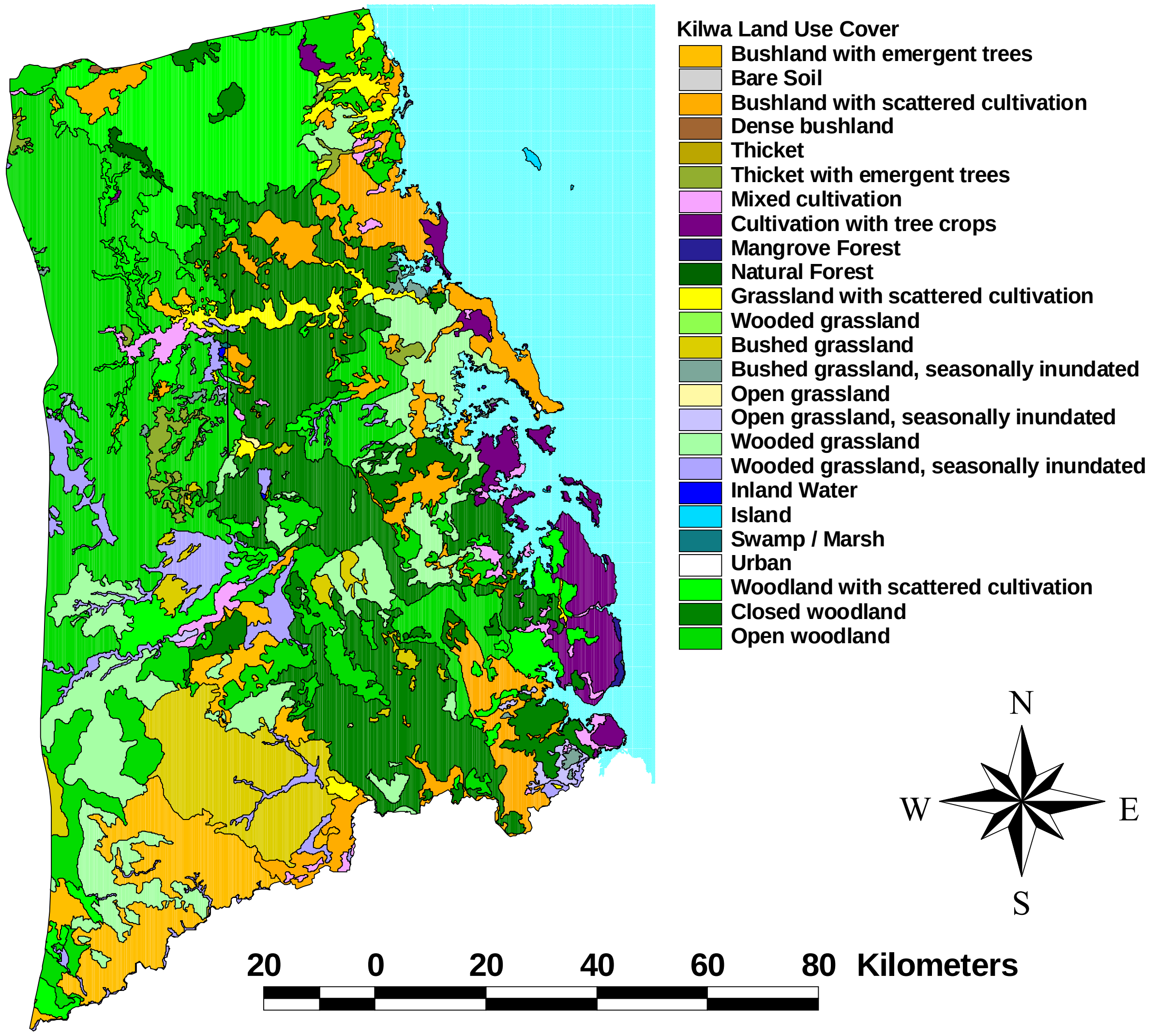

Figure 2. Land Cover in Kilwa District from 1995 LandSat images.

Close inspection of Table 4 and Table 5 shows that there is some disagreement on the total area of Kilwa District. This may be partially down to errors in estimating half squares on the 1:50,000 maps, but is likely to be indicative of real discrepancies. Given a 30 year gap between data collection, shifts in coastline, and differences in how areas such as mangrove forests are recorded, and the afore-mentioned difference in the western boundary of the District are likely to be responsible for this discrepancy. Total woodland and forest cover according to the LandSat images is 739,000ha, which is within a 2% margin of error of the figure for total forest area, 726,000ha, given by Malimbwi *et al.* (2005, definition of forest not supplied).

The reasonable consistency of the 1965 maps with habitat descriptions recorded during field surveys suggests that in most areas land-use cover has not changed markedly in the last forty years.[10] We therefore attempted to correlate the land cover classifications of the two data sources. However it is clear that some of the 1995 LandSat classifications substantially overlap the boundaries of the 1965 cover types, making any reconciliation impossible.

[10] The most obvious change is in the north of the District, where the slopes of the southernmost extent of the Matumbi Hills have been cleared for agriculture.

Data Analysis

The survey data from the fieldwork and the land cover data presented above were entered into MS Access for analysis. There the data was calibrated, and compared to different harvesting models.

Treatment of Short Transect Segments

GPS readings are subject to error. The Garmin GPS units used in this assessment quote an accuracy of <15m for 95% of readings, although in practice this is often bettered. For long transect segments this is not significant, and will average itself out, but during fieldwork some very short transect segments were recorded, indeed for some such segments the GPS readings were identical. To guard against local bias a minimum transect segment length of 40m was adopted (or about one acre in area), which fitted with surveyor perceptions[11]. Thus the length of any transect segment as reported by the GPS waypoints which was less than 40m, was subsequently fixed at 40m. This enforced minimum raised the length of 12% of the transect segments.

Note that when grouped into land cover categories the smallest surveyed area was 4320m^2 (not counting subjective transect width, see below), or 216m of transect for the Dense Bushland classification, which itself only accounts for 0.05% of Kilwa District. Most land cover categories were surveyed to an extent of several hectares or more. So the GPS precision limitations should have negligible impact on the main results.

Calibration

The calibration course showed up three potential sources of error. The most serious, and hardest to adjust for, is wrongly estimating the width of the transect, which in practice amounts to either deliberately ignoring trees inside the transect, or counting as in those just outside the transect. On the calibration course, neither of the principal surveyors[12] discounted as outside any trees which were within the 10m transect width (n=51), but counted as in many trees that actually grew outside the 10m transect.

Trees outside the Transect

Of the 46 trees on the calibration course which lay outside the transect, 43% and 20% respectively were estimated to actually lie within the transect by the two surveyors. Researcher AG included all trees within 12.6m of the transect centre, while JM excluded one tree only 10.8m from the transect line. Both researchers' worst error was including a tree 13.9m from the transect line. The subjective estimates of transect width are illustrated in Figure 3.

We can estimate from this an effective transect width for each surveyor by considering the curve between 100% and 0% chance of tree inclusion, and setting the transect width to be the point such that for every tree the surveyor records is in but is not, they are likely to ignore one which in fact is within their subjective transect[13]. By a simple visual inspection, this was estimated at 11.75m for researcher JM, and 13.65m for AG.

Before moving on we should just pause to consider why surveyors may not maintain a 100% consistent effective transect width. Immediate context and environment play a big role in determining our subjective estimate of distance. For instance viewing objects up or down a slope will affect our estimation. We also typically tend to estimate distance in relation to other objects in our field of vision, which in a heterogeneous forest environment will be constantly varying, but we have made no attempt

[11] The surveyors generally used the principle that if they could see the other side of a new habitat when they entered it on a transect, then they did not record it as a distinct transect segment unless that short section was clearly part of a much larger patch.

[12] The two principal surveyors accounted for over 90% of the estimates, and so we have confined our discussion and analysis to those two.

[13] I.e. so that the area under the curve which is excluded equals the area above the curve which is included.

to adjust for that here due to the excessively large set of calibration data which would be required to do so. However the size of the object itself will have some kind of impact, especially where the object is unusually sized.

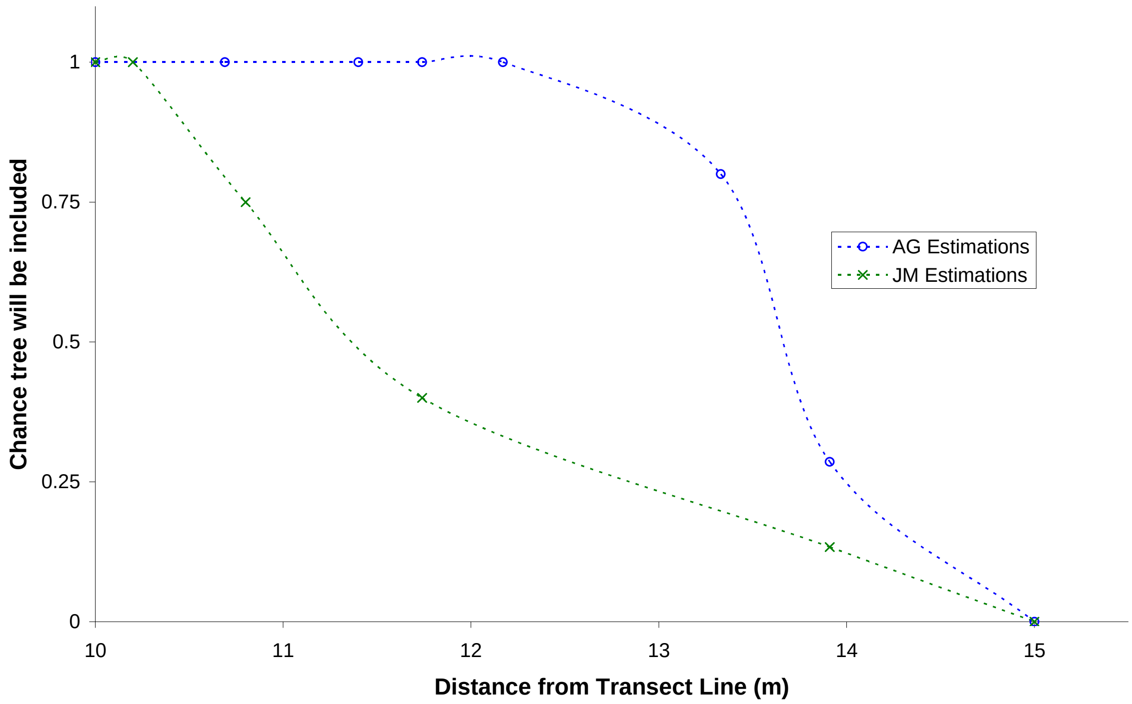

Figure 3. Subjective transect widths as experienced by surveyors. Data points selected for each researcher to give a smooth approximation of likelihood of tree inclusion. Zero probability for each researcher fixed at 15m width. Based on 35 trees between 10m and 15m distant from the transect line.

In this case we are concerned whether the size of a tree may have some impact on a surveyor's assessment as to whether it lies in or outside the transect. For our calibration course we have two indicators of tree size: DBH and Straight Length (which may be regarded as a weak proxy for tree height, implicit from Gregory *et al.* 1999). In addition we can calculate an index of apparent size by dividing the DBH by and actual distance to the tree.

We examined these three variables for all trees on the calibration course between 10 and 15m from the transect line (n=34). (From the above, we assume that neither of our principal surveyors would include any tree more than 15m from the transect line.) For each researcher they were divided into two groups according to whether the researcher believed they lay within the 10m wide transect, and a one-tailed Student's T-test was calculated to determine whether larger trees were more likely to be called inside the transect. Neither DBH nor SL showed any significant relationship for either researcher ($p > 5\%$), but while JM, whose subjective transect was more variable, was not susceptible to variation in apparent size of the tree ($p > 5\%$), AG's estimate of distance did vary with apparent size ($p < 5\%$). This is probably a result of AG's narrower band of variation[14], and inspection of tree sizes between 12.5 and 14m distance from the transect suggests that size of tree was not a decisive factor in the researcher's evaluation.[15] Hence we conclude that the subjective transect widths as given above constitute an appropriate adjustment factor, independent of tree size.

[14] I.e. most of the time researcher AG thought the transect width lay between 13m and 14m, whereas JM's subjective impression of transect width appears to vary between 10.5m and 14m.

[15] That is to say the result is primarily driven by the extremes in the 10 to 15m distance range considered. And since distance itself is a constituent variable in apparent size, it is not unsurprising that there should be some correlation with estimated distance.

Estimating Tree Size

The other two sources of error are errors in the estimation of diameter and straight bole length. We will not attempt to correct for errors in the size of smaller mpingo, but we are interested in any which are likely to be legally harvestable, i.e. have a DBH ≥ 24cm. Under-estimation is a real risk, so for this we shall be concerned with all trees with an estimated DBH of at least 20cm, i.e. where the researcher thinks it exceeds 17.5cm. This is one size class smaller than for which data was collected for all species other than mpingo *Dalbergia melanoxylon*.

135 trees on the calibration course actually had a DBH greater than 17.5cm. Only a very few of these (< 5% for each researcher) were put into an estimation size class lower than 20cm. Hence for the sake of expediency those mpingo in the bottom size classes (estimated DBH 10cm or 15cm) will be ignored in all following analysis and presentation of results except where explicitly stated otherwise.

Figure 4 and Figure 5 show field surveyors estimates compared with actual dimensions of trees on the calibration course. Simple regression of calibration course results showed that estimates of DBH by our two principle field surveyors were generally reasonably accurate and consistent. Although large sample sizes will reduce the significance of consistency errors, consistent estimates give confidence in the survey data. Both surveyors demonstrated over 85% consistency (represented by the r^2 correlation coefficient) when estimating tree diameter. Given the rounding factor introduced by forcing all estimates to the nearest 5cm, this is about as good as can be achieved.

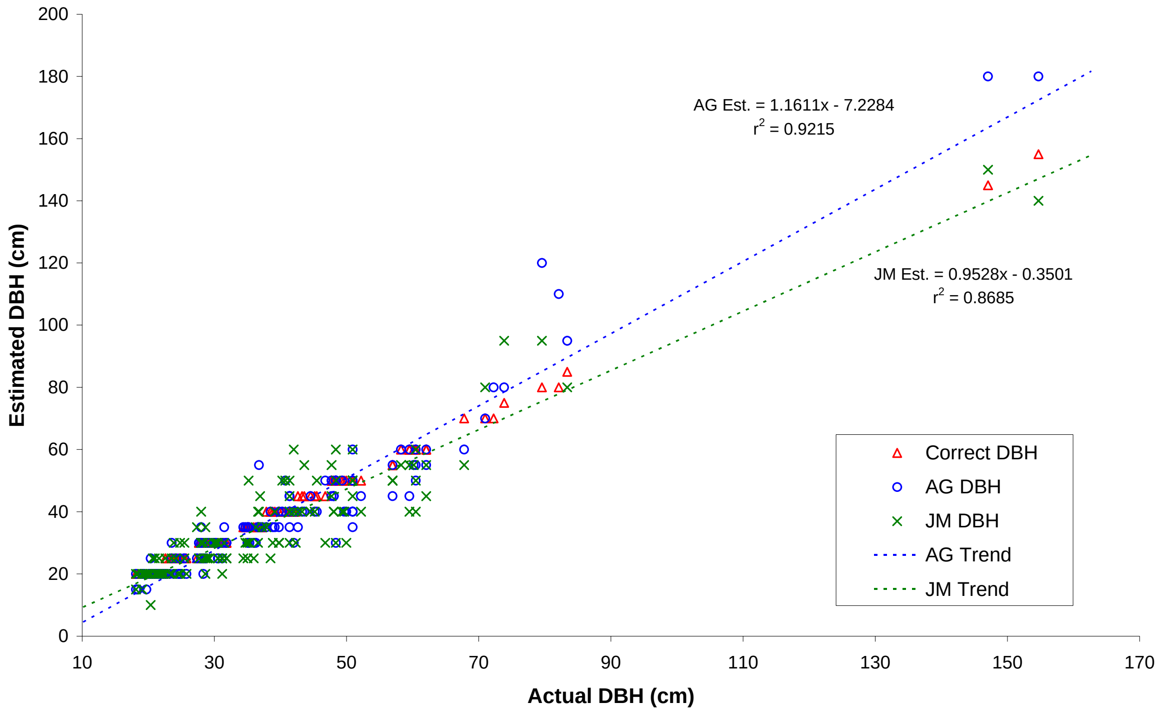

Figure 4. Estimated versus actual DBH of large trees (DBH ≥ 17.5cm) on calibration course.

The results for SL, as shown in Figure 5, are not so good; both researchers achieving a consistency around the two-thirds mark. This is partly a reflection of forcing the Y intercept to zero, which was not necessary for DBH where we are only interested in trees with DBH ≥ 17.5cm. However the loss of accuracy is not very surprising given the additional factors involved when estimating the ***potentially harvestable*** Straight Length, notably whether closer inspection reveals the timber to be unsuitable for felling. The resulting SV estimates will therefore only be accurate for large numbers of trees.

It is also possible that there could be cross effects such that a surveyor may perceive tall trees as having larger diameters than actuality and vice versa. However regression of surveyor error for DBH against actual straight length, and surveyor error when estimating SL against actual DBH showed no significant or consistent influence requiring correction ($r^2 < 5\%$ in all cases). It was similarly checked that distance from the transect line did not have a large impact on size estimates ($r^2 < 21\%$ in all cases).

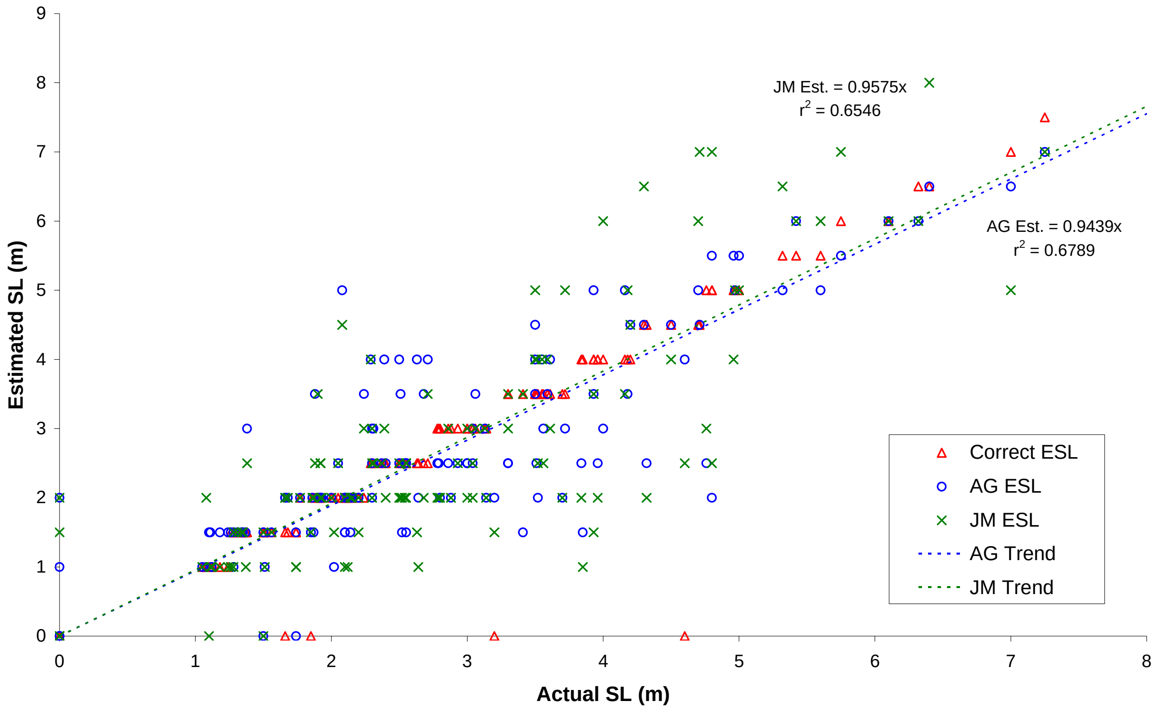

Figure 5. Estimated versus actual Straight Length of large trees (DBH ≥ 17.5cm) on calibration course.

If the estimates are reasonably consistent, or sample size is sufficiently large, then slight trends to under or over-estimate parameters can be easily corrected. For these purposes the reverse regression to that shown in Figure 4 and Figure 5 needs to be performed, in which we instead seek to minimise the error in calculating the actual DBH or SL from the researcher's estimate. Table 6 sets out the results from these regressions. Thus for instance, if given an estimate $\boldsymbol{x}$ by AG of a tree's DBH, a better point estimate of the actual DBH is given by the equation:

$$\text{Adjusted Estimate:} \quad \boldsymbol{y} = 0.79\,\boldsymbol{x} + 8.83$$

Researcher	AG	JM
DBH		
Adjustment Factor (A)	0.79	0.91
Fixed Intercept (B)	8.83	5.42
Regression Coefficient (r^2)	0.92	0.87
SL		
Adjustment Factor (A)	0.98	0.94
Regression Coefficient (r^2)	0.65	0.54

Table 6. Regression results for different researchers estimating physical dimensions of large trees. Letters (A & B) refer to the standard linear regression equation $y = Ax + B$.

This use of the reverse regression eliminates any trends for under- or over-estimation, at least for the calibration course data set[16]. However the moderate r^2 values for SL estimates mean caution must be taken in putting too much faith in single point estimates obtained in this way.

From the above data we can now compute the minimum sizes which were thus actually surveyed. For species other than mpingo this is determined by the bottom point of the 25cm DBH estimation class, i.e. 22.5cm. For researcher AG on average this works out as 26.7cm, and for JM as 25.9cm.

[16] Although not entirely for SL, where we treat all researcher estimates of zero SL as indicating actually zero SL, whereas in reality some are non-zero.

Calculating Straight Volume

We can partially assess the precision of the resulting expected figures for potentially harvestable Straight Volume (SV) obtained by each researcher, by examining the SV results obtained for the calibration course data[17], and which are depicted in Figure 6. The linear trend lines, which give more weight to the (fewer) large trees, are deliberately depicted as this disproportionate influence will be significant when we come to extrapolate expected harvested volumes across large areas.

SV is a cubic measure, and so cube roots should be taken before percentage errors are examined. We shall refer to this variable as PE-CBR-SV. After adjustments, both researchers show a mean error of less than 5% on this calibration data, although accuracy will worsen for other data sets. As with the DBH estimates, the distribution of PE-CBR-SV is not too highly skewed, but is platykurtic (i.e. less peaked than a normal distribution), nonetheless we shall subsequently treat it as Normal. The standard deviation of the PE-CBR-SV achieved by the two principal surveyors was 28% for AG and 29% for JM.

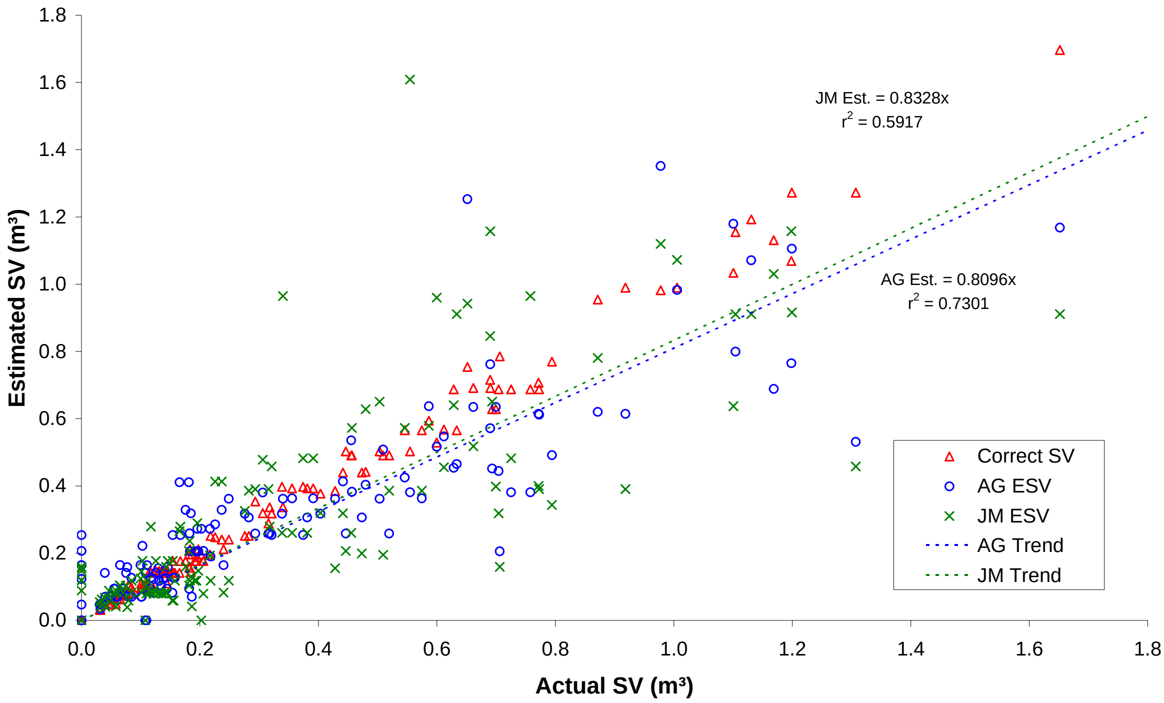

Figure 6. Estimates for Straight Volume obtained from adjusted surveyor estimates of DBH and SL, excluding two outlying largest trees.

Unobserved Trees

Usually in vegetation sampling there is no need to account for unobserved individuals such as is required when surveying animals which may remain hidden as you walk past. But in walking these rapid transects there is a real risk that some trees will be missed. Ball (2003), on whose methods ours were partly based, reported a shortage of small trees in his data set. This source of error is distinct from the above issue of incorrectly recording trees in or outside the transect, as that applies only to trees which have been noticed, whereas this source of error is concerned with individuals which have gone entirely unobserved.

Such sources of error may vary with the density of vegetation, and tend to exclude the smaller individuals. However in this case the survey team believed it was ease of pattern recognition which

[17] Since in calculating these SVs we have used the DBH and SL estimates adjusted according to regressions performed on the same set of data, this in no way compares to the robustness if we had a second set of independent calibration data, and so not too much should be read into the apparent accuracy obtained here.

played the greatest role. *Millettia stuhlmanii* and *Bombax rhodognaphalon* are quite distinctive, and mpingo is relatively common so the pattern being sought was frequently reinforced. Other trees were less distinctive or common and surveyors did not have such a good picture in their minds to trigger recognition.

Properly calibrating for this source of error would be a major exercise in itself. As it is we can only make an educated guess at its magnitude. We estimate that we probably missed 10% of all mpingo, *Millettia stuhlmanii* and *Bombax rhodognaphalon*, and around 20% of individuals of the other trees surveyed[18].

Harvesting Models

Our surveying counted all timber trees with a DBH of at least 22.5cm, and mpingo with DBH at least 7.5cm. Not all of these are legally harvestable, see Table 3 above. However, as Milledge & Kaale (2005) and others have showed, there is often a large discrepancy between what is legally harvestable, and what in practice is actually felled. To reflect this, a number of different harvesting models were defined:

- **Market Preference** – could provide a log with at least the minimum market preference diameter and length.
- **Legally Harvestable Now** – where the DBH exceeds the minimum legal requirements[19], and SL is a generally adhered to minimum based on field experience.
- **Potentially Legally Harvestable Later** – where the SL meets the requirement under the Legally Harvestable Now model, but DBH may be lower (such that as the girth increases with age the tree will be legally harvestable in future if not now). Many such individuals will not reach harvestable size.
- **Illegally Cuttable Now** – where the DBH and SL are such that, even if not legal, commercial loggers may find a market at sawmills.
- **Usable Locally** – small trees with at least the dimensions used by local villagers to meet their household requirements.[20]

An additional dummy harvesting model, **All**, includes any timber tree recorded regardless of harvestability, and is useful for population estimations. Model dimensions for each species are set out in Table 7.

Model	Dalbergia melanoxylon	Swartzia madagascariensis	Pterocarpus spp.	Milicia excelsa	Millettia stuhlmanii	Khaya anthotheca	Combretum imbibe	Afzelia quanzensis	Bombax rhodognaphalon
Market Preference	0.35 x 1.2	0.4 x 2.1	0.55 x 3.66	0.55 x 3.66	0.55 x 3.66	0.55 x 3.66	0.55 x 2.1	0.55 x 2.1	0.55 x 3.66
Legally Harvestable Now	0.24 x 1.2	0.24 x 2.1	0.45 x 2.1	0.55 x 2.5	0.45 x 2.5	0.55 x 3.66	0.24 x 2.1	0.55 x 2.1	0.55 x 3.66
Potentially Harvestable Later	0 x 1.2	0 x 2.1	0 x 2.1	0 x 2.5	0 x 2.5	0 x 3.66	0 x 2.1	0 x 2.1	0 x 3.66
Illegally Cuttable Now	0.20 x 1.0	0.24 x 2.1	0.35 x 2.1	0.55 x 2.1		0.55 x 3.66	0.24 x 2.1	0.35 x 2.1	0.55 x 3.1
Usable Locally	0.10 x 1.0		0.25 x 1.2	0.4 x 0.9	0.1 x 1.8		0.15 x 0.3	0.25 x 1.2	0.1 x 1.8

Table 7. Harvesting model definitions; minimum diameter (m) x minimum log length (m). Gaps indicate no such demand. Source: GoT (2004) and district forestry staff.

[18] We may have missed even more *Swartzia madagascarensis* but this is largely academic, as will become clear.

[19] There is no legal minimum diameter for harvesting *Millettia stuhlmanii*, but in practice very few individuals of less than 45cm diameter are felled, and so this figure was used as the *de facto* minimum.

[20] In practice only a very small proportion of such trees are used by villagers.

Determining Harvestability

Since none of the trees recorded in the survey were actually measured we cannot often be certain whether they would actually be harvestable according to any given model. Although the adjusted estimates are reasonable approximations of the true dimensions two factors combine to make a simple comparison with minimum harvesting criteria especially problem prone:

- Many of the model criteria equal or are very close to the centre figure of an estimation size class.
- Adjusting for researcher estimation trends increases or decreases the central estimate a small amount.

For example is a *Pterocarpus* with estimated DBH 45cm (i.e. between 42.5 and 47.5cm) actually legally harvestable? If it was recorded by a researcher who on average underestimates diameters by 5% then the adjusted estimate will be 47.25cm, implying the tree is legally harvestable (assuming the SL is sufficient), but if it was recorded by a researcher who tended to overestimate diameters by 5% then adjusted estimate would be 42.86cm, implying the tree is not legally harvestable.

This acute sensitivity to the identity of the researchers rules out simple reliance on the adjusted point estimate. Instead a probabilistic solution must be adopted. After adjusting for over- or under-estimation trends, the percentage errors for estimating each dimension should exhibit a roughly normal distribution. Graphical analysis suggests this is approximately true, although only the DBH estimates from the calibration course data satisfied the standard skewed-ness measure of Normality, and neither set of dimension estimates exhibited a Normal kurtosis[21]. However we shall be concerned here with determining the harvestability of single trees only as a step towards determining average harvestability of groups of trees. So in effect these non-Normal distributions will be summed, achieving a curve closer to that of the Normal distribution (by action of the Central Limit Theorem), and so we will accept the Normal distribution as a reasonable approximation.

For any given tree dimension we can thus construct a normal distribution of the likely actual dimension from the estimated figure, setting the mean to be the adjusted estimate, and a standard deviation scaled up by a factor equal to the adjusted estimate. Table 8 lists the parameters used to generate these distributions[22]. From the appropriate normal distribution can be obtained a simple probability that the actual dimension exceeds any given threshold. Hence an estimated probability that any stem section recorded by the field surveys is harvestable according to a given model can be obtained by simply multiplying the probabilities that it fulfils the diameter criterion with the probability that it fulfils the minimum straight length criterion.

Researcher	AG	JM
DBH		
Adjustment Factor (A)	0.79	0.91
Fixed Intercept (B)	8.83	5.42
Standard Deviation	14%	18%
SL		
Adjustment Factor (A)	0.98	0.94
Standard Deviation	37%	38%

Table 8. Adjustment factors and standard deviation in percentage error for different researchers estimating physical dimensions of harvestable trees.

Combining these probabilities in large data sets leads to expected total figures for the harvestability of trees and stem sections. Since, as with any such survey, only a small part of the area under

[21] In particular all the data exhibited a high kurtosis, indicating the data close to the mean are more spread out than expected in a normal distribution. This is not unsurprising when one considers the likely effects of estimating to the nearest 5cm or 0.5m.

[22] It is directly related to Table 6 which set out the regression results, but replaces the r^2 coefficient of regression with the percentage standard deviation, both a reflection of the variance in researcher estimates about the true value.

consideration was sampled[23] this does not alter the fundamental probabilistic nature of the results, although it does have a bearing on the resulting confidence intervals.

Where a tree has multiple stem sections, each potentially harvestable, the probability of the tree being harvestable, i.e. having some timber worth harvesting, is calculated from the formula:

$$P(\text{one or more stem sections are harvestable} = 1 - P(\text{no stem sections are harvestable})$$
$$= 1 - \Pi[1 - P(\text{stem section harvestable})]$$

Accuracy of Harvestability Probabilities

In order to assess the accuracy of harvestability probabilities generated by this method we compared results thus obtained from the calibration course, with the actual harvestability under a selection of different models for the trees therein[24]. As with the straight volume accuracy we must be careful not to put too much faith in the results, since the same adjustment and error functions which we will be using were themselves obtained from the same calibration data. Nonetheless it is the only data set we have available for such an exercise. To counter this, we shall mostly consider the mean harvestability rate obtained from averaging the results from each of the principal surveyors, rather than examining accuracy separately for each surveyor. This is a good approach because both surveyors have different adjustment functions, and often gave different estimates for the same tree, but the overall accuracy, as evident in the r^2 coefficient of regression, is similar on both dimensions, and hence the results can be reasonably applied to both researchers.

Considering diameter alone, the mean error increased with the size of the model parameter from 6.8% at the 24cm threshold[25], to 13.7% at the 55cm threshold, with an overall average error of 10.6%. On length, the pattern was more complex, ranging from a low mean error of 8.6% at 3.66m to a high of 22.9% at 2.1m, with an overall average error of 16.7%. Some patterns were also detectable whereby both surveyors effectively tended to under-estimate on some categories (i.e. thought fewer trees were harvestable than were), and over-estimate on others, but that could easily be an artefact of this particular data set, and so will be ignored. Moreover for many models it is the case that harvestability on one dimension was under-estimated, but over-estimated on the other dimension. Instead we must consider the combined harvestability for the various models.

The implied number of harvestable trees which were harvestable under a selection of different harvesting models are set out in Table 9. Surveyor AG appears to be more accurate for the smaller threshold harvesting models, but JM better at the larger threshold models. The overall average error rate is 31%, but we can improve on this.

Model Dimensions	24 x 1.2	35 x 1.2	40 x 2.1	45 x 2.1	55 x 3.66	55 x 2.5	45 x 2.5	55 x 2.1
AG implied count	97	55	27	18	3	6	14	7
JM implied count	85	50	27	20	4	7	16	9
Actual count	97	64	40	28	6	11	24	13
Mean Error	*7%*	*19%*	*34%*	*34%*	*38%*	*41%*	*37%*	*39%*

Table 9. No. trees on calibration course harvestable under different models: diameter (cm) x straight length (m).

It can be seen from Table 9 that both surveyors almost always under-estimate the number of harvestable trees and the mean surveyor error tends to increase as the number of harvestable trees

[23] I.e. the final results will be obtained by extrapolating out the totals obtained from the survey data.

[24] For this purpose, as with the rest of the analysis of the calibration course, the actual species of trees on the course was ignored. I.e. we assume that the whole set of trees on the calibration course is representative of any individual species for the purposes of determining estimation accuracy,

[25] That is to say of the 106 out of 133 trees on the calibration course whose DBH was actually greater than or equal to 24cm, our surveyors were out on average by ±6.2%, or ±6-7 trees.

decreases. In attempting to adjust for this under-estimation we have available only the surveyor's own effective estimate of the number of harvestable trees. This relationship is depicted in Figure 7. The regression fit is extremely good, explaining over 98% of the variation.

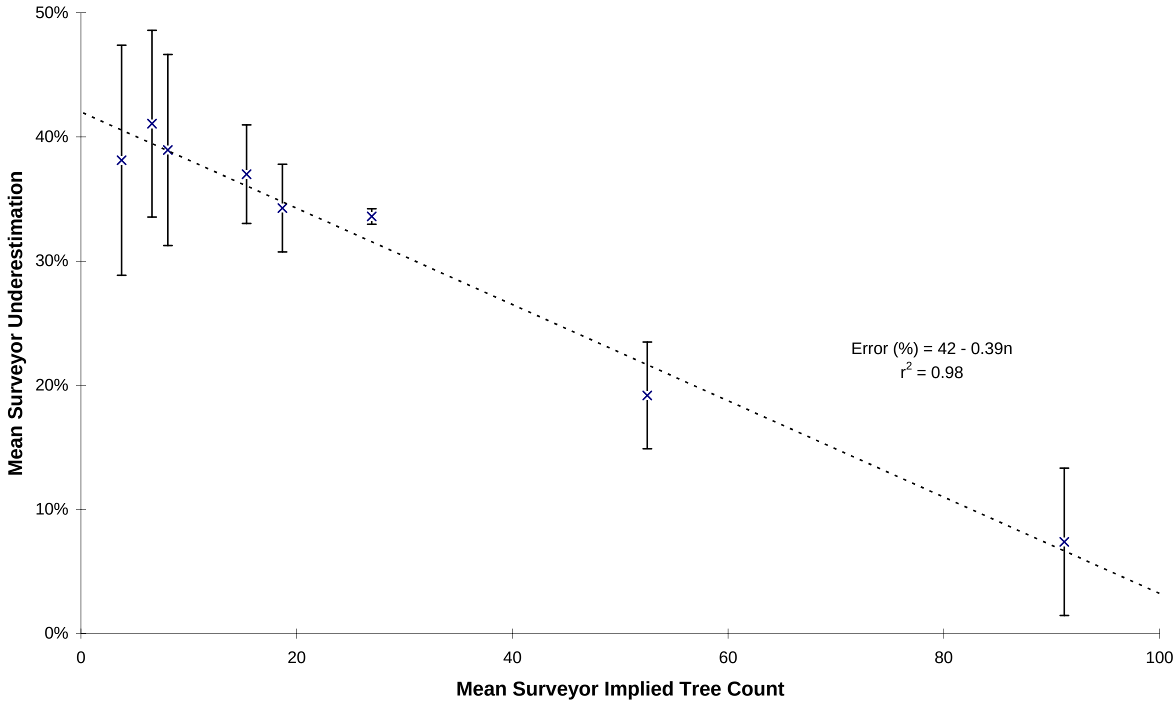

Figure 7. Relationship between mean surveyor under-estimation when computing harvestability and the mean surveyor implied count of harvestable trees. Error bars show actual error rates of the two principal surveyors.

Hence we can predict the likely rate of under-estimation when computing the mean harvestability of any set of trees from the equation:

$$\text{Under-estimation Rate (\%)} = 42 - 0.39n$$

where n is the implied number of harvestable trees, not the total number of trees in the set.[26] I.e. we obtained an adjusted estimate of number harvestable trees n' according to the formula:

$$n' = (1.42 - 0.0039n) \times n$$

If n is 108 or greater, the rate of under-estimation is apparently negligible and $n' = n$, although this result is probably related to the fact that the total number of large trees (DBH $\geq$ 24cm) on the calibration course was 133.[27]

Once we have adjusted for this under-estimation, we are left with a residual error. This also shows a negative relationship with the implied tree count, as shown in Figure 8. This simply reflects the Central Limit Theorem which states that standard error decreases as sample size increases. We can thus estimate the likely error rate after adjustment from the equation:

$$\text{Error (\%)} = 15 - 0.13n'$$

Where n' is the adjusted implied tree count calculated above. Once again the error vanishes when n becomes large, this time once n reaches 119.

[26] In this discussion it is implied that n and n' are integers, but this does not necessarily have to be the case. Indeed where n is small, rounding to the nearest integer would give misleading answers. Rounding will only be necessary when obtaining confidence limits from the Poisson distribution, see below.

[27] We assume that the relationship does not reverse itself at high n; i.e. for n above 108 we assume surveyors do not effectively over-estimate the number of harvestable trees.

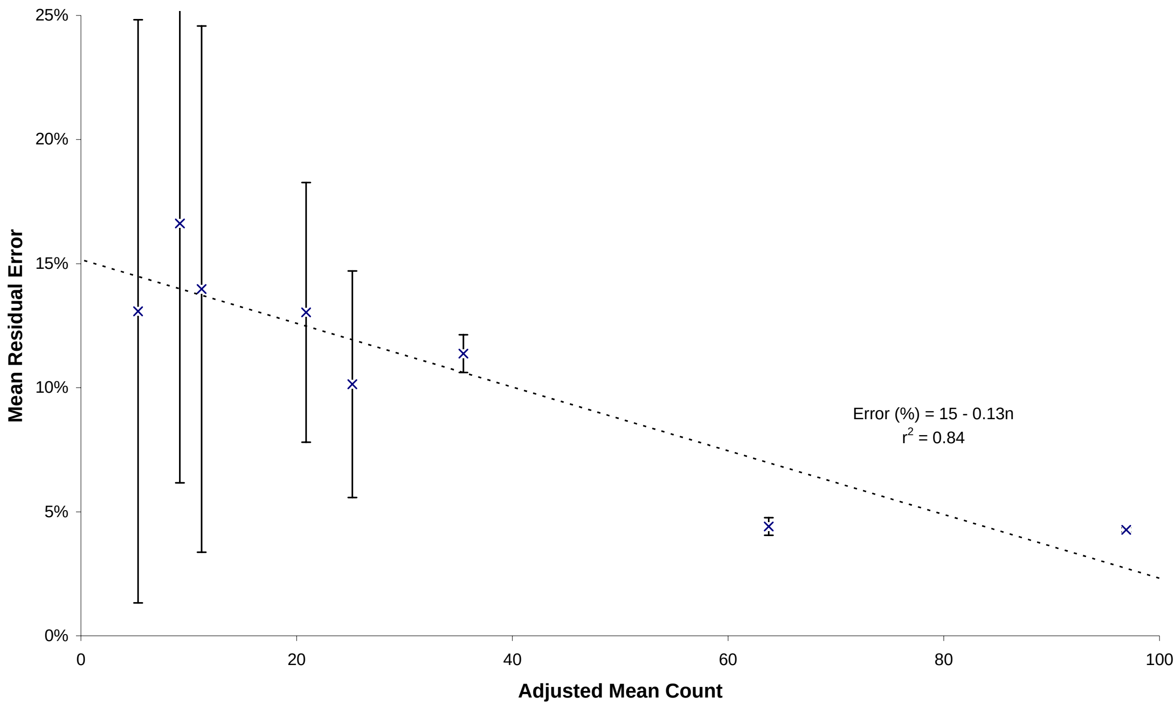

Figure 8. Relationship between mean surveyor residual error when computing harvestability and the mean adjusted surveyor implied count of harvestable trees. Error bars show actual error rates of the two principal surveyors.

The *Potentially Legally Harvestable Later* models ignore stem diameter and are concerned only with straight length. The mean surveyor underestimation / error on the straight length dimension alone is generally about half of that on both dimensions, so we shall halve the adjustment and error functions in the case of these harvesting models.

Computing the Harvestable Straight Volume

For any given stem section recorded during surveying we can calculate its expected straight volume from the adjusted estimates for diameter and straight length. This is because we expect the adjusted estimates to be Normally, and hence equally, distributed about the actual dimensions. When we consider harvestable straight volume, however, the matter is complicated by the fact that the harvestable volume is zero if the tree is not harvestable. We can approximate this by multiplying the expected straight volume of the stem section by its probability of harvestability, but this will be an underestimate since it ignores the uneven nature of harvestability; that is those cases where the stem section would not provide a harvestable quantity of timber are those at the lower end of the probability distributions of each dimension. We must solve this by finding a new mid-point.

An example shall serve to best illustrate this. Suppose a stem section had an adjusted diameter of 50cm and adjusted straight length of 1m, while the minimum diameter for harvesting under a particular model is 45cm. For the sake of this example we shall assume that straight length is not a factor in this particular model. Consulting the variability of the researcher concerned we might arrive at a harvestability probability of 60%. The expected straight volume is 0.79m³ based on a mean of 50cm, but the mean diameter of stem sections which are harvestable will be higher than 50cm, because we have excluded those 40% which are under 45cm. The solution is to consult the Normal distribution to determine which diameter coincides with a cumulative probability of 70% (i.e. half way between the 40% cut-off point and the 100% maximum). This diameter will be the mean diameter of harvestable trees, and should be used to determine the expected harvestable volume. In the case of the example that will correspond to a diameter slightly above 60cm, and hence a expected straight volume of the stem section in harvestable cases a bit over 1.13m³. Hence the expected harvestable volume of the stem section is 60% x 1.13m³ = 0.68m³.

We have already seen that the percentage error on straight volume is relatively high: around 30% when considering the cube-root, and above 50% when assessed directly. It should therefore not be surprising that the accuracy of harvestable volume figures obtained in this way is limited. Applying this method to the large trees (DBH ≥ 24cm) on the calibration course, the average error across different harvesting models was 34%. As with the probability of harvestability the harvestable volume was consistently under-estimated. However the implied mean volume of each harvestable tree[28] was more evenly distributed about the actual mean volume of harvestable trees. It is therefore reasonable to apply the same linear adjustment based on the implied number of harvestable trees, as was applied to the harvestability probability.

There is a small likelihood, particularly where *n* is low and probability of harvestability is high, that the adjusted estimate for harvestable volume obtained in this way actually exceeds the total estimated straight volume of the trees in the set. In these rare cases we shall replace the over-high estimate for harvestable volume with the simple estimated straight volume of the tree set.

The residual error on harvestable volume estimates after adjustment is depicted in Figure 9. From this we see that we can estimate the likely error rate after adjustment from the equation:

$$\text{Error (\%)} = 16.8 - 0.14n'$$

Where n' is the adjusted implied tree count, and is valid for all $n' < 120$.

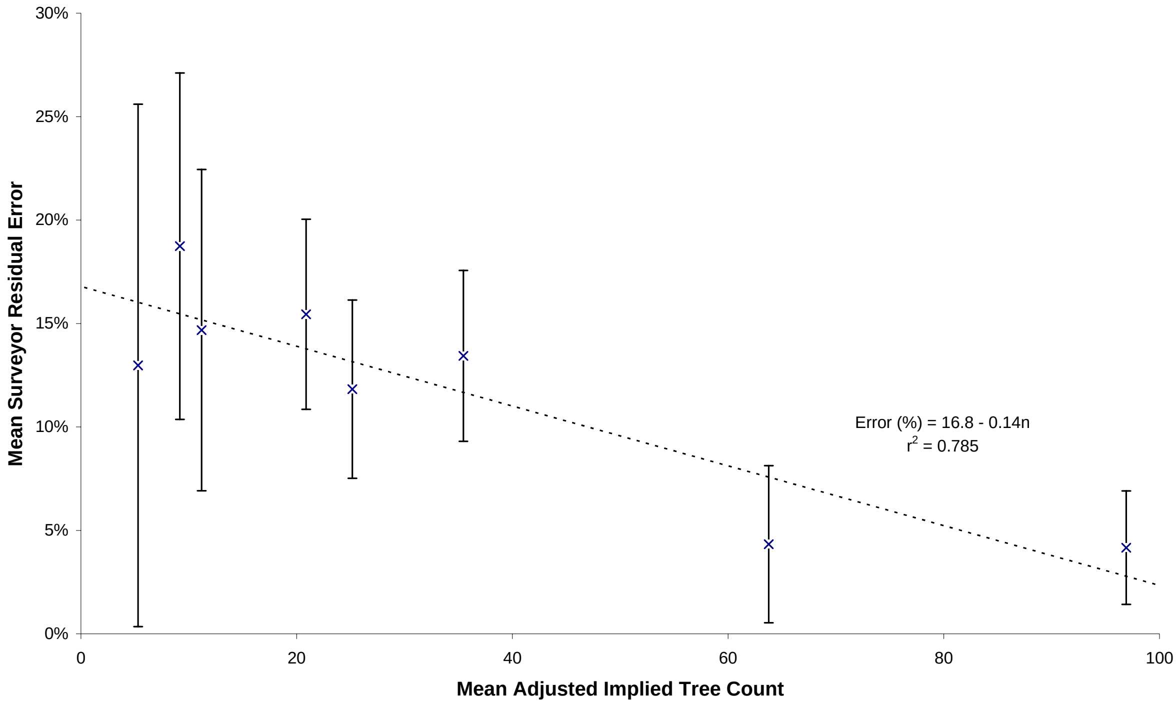

Figure 9. Relationship between mean surveyor residual error for harvestable volume and the mean adjusted surveyor implied count of harvestable trees. Error bars show actual error rates of the two principal surveyors.

Calculating Confidence Intervals

There are two types of result on which we desire to calculate confidence intervals:

a) An estimate of the number of harvestable trees.

b) An estimate of the total harvestable volume.

In determining the confidence intervals we have to take into account the following areas of uncertainty:

[28] Obtained by dividing the total harvestable volume by the original (un-adjusted) figure for the implied number of trees harvestable under the model concerned.

i) Trees not seen inside a transect.

ii) Trees wrongly counted as in or out of the transect.

iii) The extent to which the sampled area is representative of number of trees present (distribution).

iv) The probability that a surveyed tree is harvestable.

v) Variation in diameter and length estimates, and hence SV.

Each of the five must be addressed separately, such that for the two types of result we are able to compute a confidence interval of the desired accuracy. In combining multiple sources of error we will make use of the simple fact that for small α, β:

$$(1 - \alpha)(1 - \beta) \approx 1 - (\alpha + \beta)$$

That is to say that the amount of likelihood excluded in a confidence interval is summed when several are combined, e.g. if one has a 95% CI for the mean of a length measurement and a 95% CI for the mean of an independently determined width, then one can be 90% certain that mean area lies within in the CI constructed by multiplying the respective lower and upper bounds of the component CIs.

Dealing with Tree Sets

In computing stocks figures across the whole district our approach is to determine tree and harvestable volume density for each species and each land cover class and then extrapolate out from the sampled area within each class to obtain totals for the entire area under such a land cover, and hence a total for the whole of Kilwa District. We thus need to compute a confidence interval for each result for each land cover class. In the following discussion we will therefore be mostly dealing with sets of trees, all found within a single land cover class. When considering physical estimates, we shall be concerned with the mean error on such estimates within a given tree set. In doing so we shall use the Central Limit Theorem which states that for samples of size n drawn from a distribution with mean μ and finite variance σ^2, the distribution of the sample means is approximately $N(\mu, \sigma^2/n)$.[29] Thus for a given set of n surveyed trees, we expected the mean error on an adjusted estimate to be distributed $N(0, s^2/n)$, where s is the standard deviation of the researcher's estimation error for the measurement concerned. Thus the confidence intervals will be much tighter for land cover classes in which a large number of trees were seen during surveying.

In order to calculate total stocks for the whole district we will sum results for each land cover class using the simple rule for independent random variables X and Y:

$$E(X + Y) = E(X) + E(Y)$$

When working out confidence intervals, though, we cannot simply sum the lower and upper bounds[30]. Confidence intervals effectively report the spread, or standard deviation s of the result. For independent X and Y this can be obtained by the relationship:

$$\mathrm{Var}(X + Y) = \mathrm{Var}(X) + \mathrm{Var}(Y) \qquad \text{where } \mathrm{Var} = s^2$$

In determining the variance of X and Y we shall assume our constituent variables are approximately normally distributed, and that the difference between the mean and the 95% confidence limits is therefore $1.96s$.[31] However this will fail where X or Y is significantly skewed, which preliminary analyses showed was quite common. We shall therefore perform the calculation separately for the upper and lower limits, i.e. computing different variances for values greater than the mean and less than the mean.

We will now discuss the general treatment of the five sources of uncertainty, and produce methods to obtain the two results (**a**) and (**b**).

[29] If n is approximately Normally distributed, as we shall generally be assuming, then this holds for relatively low n.

[30] In fact this would generate wider confidence intervals than is necessary.

[31] Or $1.28s$ in the case of 80% confidence limits and $1.44s$ for 85% confidence limits.

Trees not seen inside a transect

As discussed above we can only guess at how severe is this source of error. However a clear lower bound is the possibility that no trees (of a given species in a given habitat) were missed, so that the lower boundary is not adjusted by the appropriate factor. At the upper end, we estimate that we may have possibly missed double the number of trees, so the adjustment value will be doubled to obtain the upper 95% boundary. E.g. we expected to miss 10% of mpingo, so the mean is multiplied by 1.10, the lower confidence limit stays as is, and the upper 95% confidence limit is multiplied by 1.20.

Trees wrongly counted as in or out of the transect

The earlier analysis established that both researchers experienced a subjective transect between 10m and 15m wide, i.e. they included all trees within 10m, and no trees beyond 15m from the transect line. This was ultimately based on the 34 trees on the calibration course which lay between 10m and 15m distant. We can thus treat these 34 trees as sample points in estimating the mean subjective width of the transect. For instance, the Standard Error of the mean of these 34 sample points is 0.26m suggesting that for a surveyor whose subjective estimation of transect width exhibited a roughly linear variation between 10m and 15m, a 95% confidence interval for the 'mean' subjective distance is ±0.51m.

We could use this as a guide to construct 95% CIs for the subjective width for each researcher, but in fact we can narrow down the variable range for each researcher to 15 trees (AG) and 27 trees (JM). We conclude that we can be 95% confident that JM's subjective transect width lay within ±0.42m of the estimated mean of 11.75m (i.e. between 11.33m and 12.17m), while for AG the respective boundaries are 13.47m and 13.83m. Under this operation the total surveyed area is seen to lie between 419ha and 443ha with 95% confidence, a variation of ±2.8% about the point estimate.

Sampled area is representative of overall distribution

For this a Poisson distribution is used. If the total surveyed area is A hectares, and in that area X individuals of a species were found, then the unbiased estimate of the population density $D = X / A$. We can then calculate the confidence limits as to what is the actual D using the following formulae:

$$L_1 = \frac{\chi^2_{(1-\alpha/2),2X}}{2A} \qquad L_2 = \frac{\chi^2_{(\alpha/2),2X}}{2A}$$

This applies equally whether X is the total number of trees of a given species, or the number computed as being harvestable according to a particular model. We will take confidence limits after applying the adjustment for surveyor under-estimation of harvestability discussed above.

Variation in physical estimates

In considering the effect of variation in these physical estimates it may in certain circumstances be possible to use the Central Limit Theorem as discussed above to obtain a mean error for each tree set within a land cover class, and from this to calculate a confidence limit for each dimension estimate on each tree within the tree set. However this is only appropriate when the results will be directly combined additively. They could not be used to compute harvestability (which would thereby collapse to a definite yes or no) or harvestable volume.

Error in computing the straight volume

For this we shall once again consider the set of surveyed trees which were recorded in the land cover class in which we are interested. The above analysis of volume calculations reduced the error to a single variable PE-CBR-SV, which is roughly Normal, and for each researcher we have deduced a figure for the standard deviation s[32]. Now we shall use the Central Limit Theorem to calculate upper and lower confidence limits for the mean PE-CBR-SV. These confidence limit error values will then be

[32] Where the transects contributing trees to the tree sets were walked by different surveyors we shall take a weighted average. In practice the actual variances for each researcher are quite similar, so this will have a small impact.

applied to the cube root of the SV of each tree in the set, to obtain confidence limits for the SV of each tree *within the context of this set of trees*. Finally the confidence limits can be summed to obtain confidence limits for the total SV of the set of trees, and extrapolated as appropriate. It can also be noted that by applying the PE-CBR-SV confidence limit shifts separately to each tree, and then cubing, we are maintaining the strong influence of larger trees over smaller ones in determining total straight volume.

Error in computing the harvestable proportion

In the above discussion on harvestability we derived a strong relationship between the expected number of harvestable trees, and the standard error of the (adjusted) proportion of trees which are harvestable. In order to use this to compute a confidence interval we must multiply the result by 1.96 (to transform the standard error to the deviation appropriate to the 95% confidence level). Hence we can calculate the confidence interval due to errors in estimating physical dimensions from the following formula:

$$\text{Confidence Interval (\%)} = \pm \{ 29.7 - 0.25X \}$$

Where X is the expected number of harvestable trees under a given model, after adjustment for under-estimation. This interval vanishes to zero once X reaches 119, so we shall fix as a minimum the error on 100 trees which is 4.7%. As previously noted the models for *Potentially Legally Harvestable Later* ignore the diameter dimension. In this case we will take note of the fact that the average standard error on the length axis only is roughly half that of models based on both dimensions. We will therefore halve the confidence interval given above in these cases.

Confidence intervals for the number of harvestable trees

The sources of error affecting this are the Poisson distribution function and the error function of harvestability. The combined effect of the two confidence intervals produces a 90% confidence interval. The additional variations from missing trees inside the transect and subjective transect width are then applied at the end, to reach a final interval appropriate to the 80% confidence level.

Confidence intervals for the total harvestable volume

In the case of the dummy model *All*, where harvestability is always 100%, the above noted method for computing confidence limits on the tree straight volume shall be applicable. For all other models we shall use the residual error function for the adjusted harvestable volume in the same manner as we used the residual error function of the harvestable proportion:

$$\text{Confidence Interval (\%)} = \pm \{ 33.6 - 0.28X \}$$

Where X is the expected number of harvestable trees under a given model, after adjustment for under-estimation. As before we shall fix as a minimum the error on 100 trees which is 5.6%. We shall not halve the error rate for *Potentially Legally Harvestable Later* models.

For small n in particular we may find that the lower confidence limit generated in this way is often higher than the bottom confidence limit for the total straight volume for all the trees in the set. In these cases we shall simply adopt the bottom confidence limit for the total straight volume.

Finally we shall apply the limits for missing trees inside the transect and subjective transect width, to derive an interval appropriate to the 85% confidence level.

Results

Except where explicitly stated, results for mpingo *Dalbergia melanoxylon* exclude trees where estimated DBH was less than 20cm. However this still includes one size class more than was surveyed for other timber species.

Stumps

A total of only 4 stumps were recorded during surveying, all mpingo. One individual had 5 secondary stems growing around the main stem which had been cut. Together the stumps represent less than 1% of all the mpingo seen. Stumps are therefore excluded from all the following analysis. The one tree with standing secondary stems is retained.

Recorded Timber Trees

Table 10 presents a summary of the trees observed by species. It can instantly be seen from this that *Swartzia madagascariensis* and *Khaya anthotheca* were too rare for any meaningful results to be computed, and data set size problems may arise for *Combretum imberbe*, *Milicia excelsa* and *Bombax rhodognaphalon*, especially when dealing with sub-sets of the data on a habitat-by-habitat basis. Mpingo was by far the commonest tree seen.

Species	Total Freq.	Mean DBH	Max DBH	Proportion Legally Harvestable
Dalbergia melanoxylon *	432	36	104	48%
Swartzia madagascariensis	6	40	48	90%
Pterocarpus spp.	176	41	152	22%
Milicia excelsa	36	38	64	7%
Millettia stuhlmanii	277	33	56	1%
Khaya anthotheca	6	62	128	33%
Combretum imberbe	20	43	88	27%
Afzelia quanzensis	94	43	97	7%
Bombax rhodognaphalon	46	53	142	26%

Table 10. Summary encounter data for surveyed species. DBH figures in cm, and refer to largest stem only. Legally harvestable probabilistic measure included as an indicator of what proportion of each species were large size. Due to nature of calculation this may not represent a whole number of trees.
*** For consistency figures for *Dalbergia melanoxylon* only include trees down to estimated DBH of 25cm. A total of 608 *Dalbergia melanoxylon* were seen with a DBH of 20cm or greater, of which 41% were legally harvestable.**

Size distributions for each of the four commonest species are shown in Figure 10. There is a notable lack of smaller *Pterocarpus spp.*, and also to a lesser extent of *Afzelia quanzensis* and the less common species taken together. Figure 10 also explains the extremely low proportion of *Millettia stuhlmanii* which are legally harvestable given in Table 10 as a combination of a healthy population of smaller individuals combined with demanding *de facto* minimum harvesting requirements.

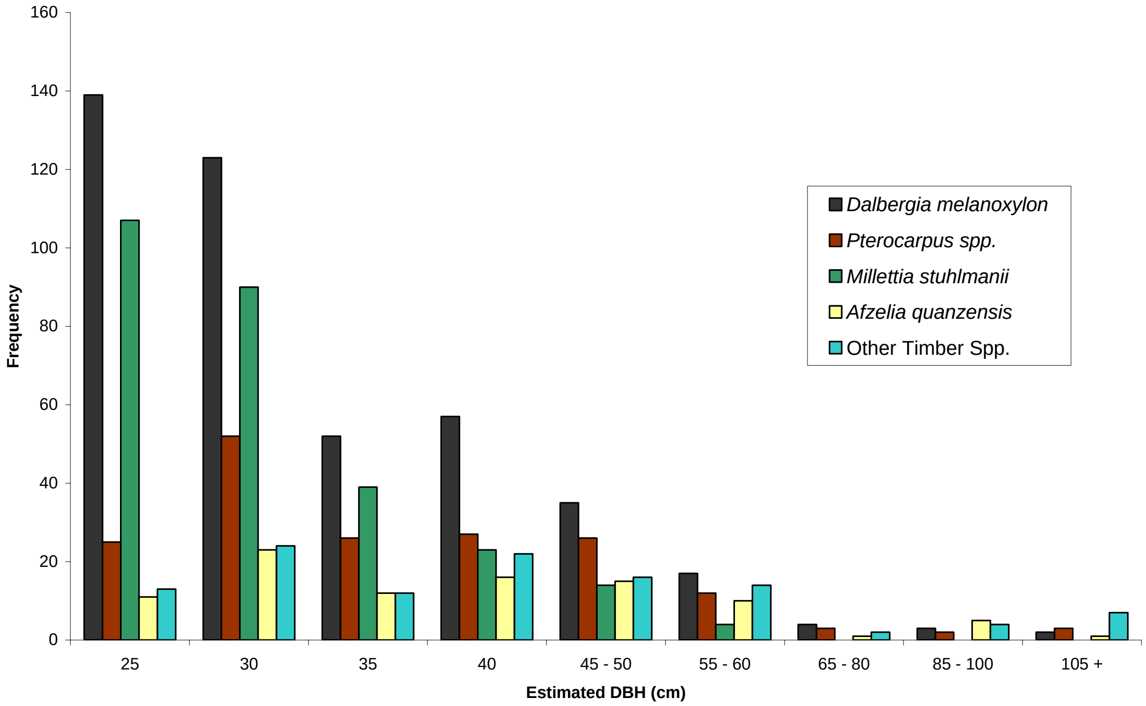

Figure 10. Size distribution of observed timber trees. DBH of largest stem used. Note varying class widths. For consistency excludes mpingo with DBH less than 25cm.

Note that Figure 10 depicts the DBH of the largest stem; many of these trees, especially mpingo, are multi-stemmed, as set out in Table 11. Mpingo stems are often branched and not straight, and so may contain more than one stem section, and this is borne out by the significantly higher mean number of stem sections per tree than mean stems. This situation is much rarer in the other species under consideration as evidenced by identical or near-identical mean stem sections and mean stems per tree.

Species	Mean Stems per Tree	Mean Stem Sections per Tree
Dalbergia melanoxylon	1.41	1.78
Pterocarpus spp.	1.11	1.12
Milicia excelsa	1.22	1.22
Millettia stuhlmanii	1.24	1.25
Combretum imberbe	1.75	1.75
Afzelia quanzensis	1.09	1.09
Bombax rhodognaphalon	1.02	1.02

Table 11. Average number of stems and potentially harvestable stem sections on observed trees.

Minimum Sample Sizes by Land Cover

Inspection of the data shows that mpingo *Dalbergia melanoxylon* was most wide-ranging in its habitats, occurring in all seven of the land cover classes derived from the 1965 topographic maps, and in various categories of Bushland, Grassland, Woodland and Cultivated Land in the 1995 LandSat classification. In contrast the three least common species, *Swartzia madagascariensis*, *Khaya anthotheca* and *Combretum imberbe*, were each found in only one or two land cover classes in both land cover classifications. Other species exhibited an intermediate habitat diversity.

For the commoner species, the land cover classifications we have may not be the most appropriate for determining a total count of the species. While we cannot compensate for divisions not represented in the classifications, we can remove those which are inappropriate.

There are several cases across all species and both land cover classifications where only one or two individuals of a species were recorded in a given land cover class. Equally there are one or two rarer cases of exceptionally high apparent density of a certain species in a certain land cover class. In both types of case, if the transects only occasionally passed through this land cover class, these results may simply be statistical accidents. The overall accuracy of the stock count will therefore be improved, and narrower confidence intervals obtained, if these under-surveyed strata can be combined with other strata. However, as tree species differ in their habitat preferences, the choice of which land cover classes to merge must be made on a species by species basis.

We examined every example of where the total number of trees recorded in a land cover class was less than 10. If the surveyed area was also small, a new merged land cover category was created, merging the under-surveyed land cover category with other similar ones. To avoid any inappropriate merges of unlike habitats (for the species concerned), we computed the Poisson probability of encountering the actual number of timber trees observed in each constituent land cover category of each newly created merged category, and the merge was rejected if the probability lay below 5% or above 95% (i.e. a two-tailed test at 10%). This caused a number of potential land cover merges to be discarded.[33] The remaining land cover combinations, which were accepted, are listed in Table 12.

Data Source	Merged Land Cover	Component Land Covers	Applicable Species
1965 Maps	Thicket & Scrub	Thicket Scrub	*Pterocarpus spp., Afzelia quanzensis*
1995 LandSat	All Bushed & Wooded Grassland	Bushed Grassland Wooded Grassland (both possibly seasonally inundated)	*Dalbergia melanoxylon*
	Cultivated Land	Mixed Cultivation Cultivation with Tree Crops	*Dalbergia melanoxylon*
	General Thicket	Thicket – with and without Emergent Trees	*Dalbergia melanoxylon,* *Pterocarpus spp., Afzelia quanzensis,* *Bombax rhodognaphalon*
	Thicket & Dense Bushland	Dense Bushland Thicket – with and without Emergent Trees	*Millettia stuhlmanii*
	Open Woodland (maybe scattered cultivation)	Open Woodland Woodland With scattered cultivation	*Afzelia quanzensis*
	Dry Bushed & Wooded Grassland	Bushed Grassland Wooded Grassland	*Pterocarpus spp.*

Table 12. Merged Land Cover Classes, their component land cover classes, and applicable timber species.

Demonstration Calculation for Mpingo

We shall illustrate the previously described analysis in the case of mpingo, the most numerous species encountered in our study area.

A total of 608 mpingo were seen for which the DBH was estimated to be 20cm or greater. The distribution of these trees is set out in Table 13. As expected, distribution is uneven across the different categories of land cover.

[33] One exception is in the All Bushed & Wooded Grassland category for mpingo, where the conclusion of the Poisson tests that mpingo grows in both bushed and wooded grassland, and in seasonally inundated wooded grassland, but not in seasonally inundated bushed grassland was rejected as nonsensical from an ecological perspective, and the merged land use retained. This problem may have been caused by the land cover classifications being obtained subsequent to the field work, and then the transect segments classified according to contemporaneous habitat descriptions, which may not have always included all relevant detail to the Hunting Technical Services classification of land cover. Alternatively it could just be regarded as a classic example of a Type I error.

Land cover	# Trees seen
1965 Maps	
Forest	1
Scattered Trees	324
Scrub	44
Settlement	2
Thicket	38
Water	2
Woodland	197
1995 LandSat Image	
All Bushed & Wooded Grassland	114
Bushland With Emergent Trees	3
Bushland With Scattered Cultivation	0
Closed Woodland	22
Cultivated Land	10
Dense Bushland	0
General Thicket	19
Grassland with Scattered Cultivation	0
Natural Forest	0
Open Grassland	0
Open Grassland Seasonally inundated	0
Open Woodland	431
Woodland With Scattered Cultivation	9

Table 13. Actual frequency of observed mpingo by land cover.

The next step is to compute the confidence limits from the Poisson Distribution for the likely number of trees in any area equal to the exact area of the transect segments surveyed, and then calculate the expected number of trees (by adding on 0/10/20% for those not seen). From here we can calculate the point estimate and confidence interval for density in each land cover category, but in doing so the confidence interval widens slightly as we must incorporate the effects of subjective transect width.[34] Moreover at each step along the way, as each variable factor is introduced, the overall confidence level also decreases by 5%. The results are set out in Table 14. Note how the categories where many mpingo were found have proportionately tighter confidence limits.

Land cover	Frequency		Density (ha^{-1})	
1965 Maps				
Forest	1.1	(0.0 - 4.4)	0.030	(0.001 - 0.124)
Scattered Trees	356.4	(289.7 - 432.3)	2.250	(1.767 - 2.829)
Scrub	48.4	(32.0 - 69.5)	0.732	(0.470 - 1.083)
Settlement	2.2	(0.2 - 6.7)	0.423	(0.046 - 1.303)
Thicket	41.8	(26.9 - 61.2)	1.446	(0.890 - 2.218)
Water	2.2	(0.2 - 6.7)	0.462	(0.050 - 1.422)
Woodland	216.7	(170.4 - 270.5)	1.609	(1.240 - 2.051)

[34] We divide the lower limit of the expected number of trees by the upper limit of the area surveyed, and *vice versa*.

Land cover	Frequency		Density (ha^{-1})	
1995 LandSat Image				
All Bushed & Wooded Grassland	125.4	(94.0 - 163.0)	2.762	(1.965 - 3.796)
Bushland With Emergent Trees	3.3	(0.6 - 8.7)	0.193	(0.036 - 0.516)
Closed Woodland	24.2	(13.8 - 38.5)	0.317	(0.178 - 0.512)
Cultivated Land	11.0	(4.8 - 20.5)	0.274	(0.118 - 0.517)
General Thicket	20.9	(11.4 - 34.1)	0.793	(0.414 - 1.362)
Open Woodland	474.1	(391.3 - 567.2)	2.484	(1.989 - 3.066)
Woodland With Scattered Cultivation	9.9	(4.1 - 18.9)	0.554	(0.225 - 1.083)

Table 14. Expected frequency and implied density of mpingo by land cover with confidence intervals (90% confidence for frequency, 85% for density). Land cover classes where no mpingo were found are excluded.

Combining the estimated densities with the area of Kilwa District under each type of land cover produces an estimate of the total stocks. When based on the land cover depicted on the 1965 maps this works out at 1.29 (1.07 – 1.58) million mpingo trees, while under the 1995 LandSat classification the result is 1.75 (1.48 – 2.10) million mpingo in Kilwa District, with an 85% confidence level in each case.

For each category we now construct a tree set comprising all mpingo seen on transect segments within that class of land cover. For each such tree set, and for each harvesting model, we must then compute the expected mean harvestability and the expected harvestable volume, and confidence intervals for each. By way of an example, we shall explore this in detail for the three mpingo seen in Bushland with Emergent Trees (1995 LandSat classification) and with regards to the *Legally Harvestable Now* model. Those three mpingo, which in our database have the identification numbers 88, 90 and 883, were recorded on two separate transects, on both of which the lead surveyor was AG. Their estimated dimensions and adjusted estimates are given in Table 15. Confidence limits in the context of this tree set are set out in Table 16 for comparison.

Tree ID	DBH (cm)	Stem Section	Diameter (cm)	Straight Length (m)	Straight Volume (m^3)
88	20 / 24.7	1	20 / 24.7	3.0 / 2.95	0.14
90	25 / 28.7	1	25 / 28.7	1.0 / 0.98	0.06
883 *	25 / 28.7	1	25 / 28.7	2.0 / 1.96	0.12
		2	25 / 28.7	0.5 / 0.49	0.03

Table 15. Dimensions of mpingo observed in Bushland with Emergent Trees (Estimate / Adjusted Estimate). * Tree no. 883 is single stemmed but has two straight sections of trunk.

Tree ID	Stem Section	Diameter (cm)	Straight Length (m)	Straight Volume (m^3)
88	1	20.7 – 28.7	1.7 – 4.2	0.06 – 0.27
90	1	24.0 – 33.3	0.6 – 1.4	0.03 – 0.12
883	1	24.0 – 33.3	1.1 – 2.8	0.05 – 0.24
	2	24.0 – 33.3	0.3 – 0.7	0.01 – 0.06

Table 16. Confidence limits for dimensions of mpingo observed in Bushland with Emergent Trees.

The first step is to calculate the probability of harvestability and expected harvestable volume of each tree in the tree set; these are detailed in Table 17.

Tree ID	Stem Section	Harvestability	Harvestable Volume (m^3)
88	1	54%	0.09
90	1	24%	0.02
883	1	74%	0.11
	2	0%	0.00

Table 17. Probability of harvestability and expected harvestable volume of mpingo observed in Bushland with Emergent Trees under the *Legally Harvestable Now* model.

Clearly the harvestability of Tree 883 is determined solely by stem section 1. From this we can see that the mean harvestability of the three mpingo in Bushland with Emergent Trees under the *Legally Harvestable Now* model is 51%, and the total harvestable volume is $0.22m^3$.

The unadjusted expected number of harvestable trees is therefore 51% x 3 = 1.53 trees. Applying the adjustment to counter surveyor under-estimation we find we must multiply this figure by

$$(142 – 0.39 \times 1.53) / 100 = 1.41$$

to obtain an adjusted estimate of 2.16 trees, which is equivalent to a harvestability of 72%. The estimate for total harvestable volume must be similarly adjusted to obtain a new estimate of $0.31m^3$.

Rounding our adjusted estimate for harvestable trees to 2 individuals we then look up the corresponding Poisson 95% confidence interval which ranges from 0.24 to 5.57 trees. In order to calculate confidence limits for the harvestability we must also consider the variation due to residual surveyor error in estimating tree dimensions, which is ±28.8%. Hence our confidence interval for the number of harvestable trees is from 0.71 x 0.24 = 0.17 trees to 1.29 x 5.57 = 7.18 trees at the upper end. (This is an extreme case due to the very small number of trees in this set.) We can express this as a harvestability proportion by examining the Poisson confidence limits for the number of trees seen – three – which are 0.62 and 7.22 trees. The lower confidence limit for harvestability is thus 0.17 / 0.62 = 28%, and that at the upper limit is 99.6%. In a similar we calculate the confidence limits for total harvestable volume from the residual error function which results in a ±33% interval, and hence limits of $0.21m^3$ and $0.41m^3$. This lower limit, however, is greater than the lower limit for the total straight volume of the three trees, and so we adopt the lower figure of $0.14m^3$.

The results for all land cover classes under the *Legally Harvestable Now* model are set out in Table 18. Notice how the confidence limits for some land cover classes are very wide. Many mpingo were seen whose dimensions were quite close to the thresholds for legal harvesting, hence the wide variability. Other harvesting models and other species have considerably tougher requirements, and the confidence intervals will not be so wide.

Land cover	Mean Harvestability		Total Harvestable Volume (m^3)	
1965 Maps				
Forest	79%	(71% - 100%)	0.1	(0.0 - 0.1)
Scattered Trees	34%	(32% - 38%)	24.8	(26.2 - 26.2)
Scrub	71%	(51% - 90%)	14.4	(10.8 - 17.8)
Settlement	100%	(71% - 100%)	0.7	(0.4 - 0.9)
Thicket	58%	(39% - 78%)	4.7	(3.4 - 6.0)
Water	69%	(7% - 86%)	0.6	(0.3 - 0.8)
Woodland	51%	(50% - 56%)	34.1	(36.1 - 36.1)

Land cover	Mean Harvestability		Total Harvestable Volume (m^3)	
1995 LandSat Image				
All Bushed & Wooded Grassland	49%	(38% - 61%)	15.1	(12.4 - 17.8)
Bushland With Emergent Trees	72%	(28% - 100%)	0.3	(0.1 - 0.4)
Closed Woodland	81%	(58% - 100%)	9.0	(6.5 - 11.3)
Cultivated Land	83%	(52% - 100%)	2.0	(1.4 - 2.6)
General Thicket	67%	(45% - 93%)	3.3	(2.3 - 4.3)
Open Woodland	39%	(38% - 43%)	49.3	(52.0 - 52.0)
Woodland With Scattered Cultivation	52%	(28% - 83%)	0.7	(0.5 - 1.0)

Table 18. Expected mean harvestability and total harvestable volume of observed mpingo which is legally harvestable now with confidence intervals (90% for harvestability, 95% for harvestable volume).

From here we can calculate the expected number of harvestable trees and harvestable volume in the surveyed area of each land use. This differs from the above in that it incorporates the additional variability according to the number of trees it is thought might have been missed during surveying. For our sample group of mpingo in Bushland with Emergent Trees we expect an average of 2.4 trees (85% CI: 0 to 8.6 trees) and an expected harvestable volume of $0.34m^3$ (90% CI: $0.14m^3$ to $0.50m^3$). For our penultimate step we now compute the expected density of harvestable trees and expected harvestable volume per hectare for each land cover. The total area surveyed in the Bushland with Emergent Trees land cover class was 17.1ha (95% CI: 16.8 – 17.3ha), and hence the expected density of mpingo which is legally harvestable now in this land cover class is 0.14 trees/ha (80% CI: 0.01 to 0.51 trees/ha) and the expected harvestable volume per hectare is 0.020 m^3/ha (85% CI: 0.008 to 0.030 m^3/ha).

Details of the expected density and volume per hectare for all land cover classes are set out in Table 19. Our confidence level has dropped to 80% due to the variation in subjective transect width.

Land cover	Density (trees / ha)		Volume per Hectare (m^3 / ha)	
1965 Maps				
Forest	0.02	(0.00 - 0.12)	0.00	(0.00 - 0.00)
Scattered Trees	0.75	(0.57 - 1.07)	0.17	(0.16 - 0.21)
Scrub	0.52	(0.24 - 0.98)	0.24	(0.16 - 0.33)
Settlement	0.42	(0.03 - 1.30)	0.14	(0.07 - 0.21)
Thicket	0.84	(0.35 - 1.73)	0.18	(0.11 - 0.26)
Water	0.32	(0.00 - 1.22)	0.13	(0.05 - 0.19)
Woodland	0.81	(0.62 - 1.15)	0.28	(0.26 - 0.33)
1995 LandSat Image				
All Bushed & Wooded Grassland	1.36	(0.75 - 2.31)	0.37	(0.26 - 0.50)
Bushland With Emergent Trees	0.14	(0.01 - 0.51)	0.02	(0.01 - 0.03)
Closed Woodland	0.26	(0.10 - 0.51)	0.13	(0.08 - 0.18)
Cultivated Land	0.23	(0.06 - 0.52)	0.05	(0.03 - 0.08)
General Thicket	0.53	(0.18 - 1.27)	0.14	(0.08 - 0.20)
Open Woodland	0.97	(0.76 - 1.32)	0.28	(0.26 - 0.34)
Woodland With Scattered Cultivation	0.29	(0.06 - 0.90)	0.05	(0.03 - 0.07)

Table 19. Expected density and expected harvestable volume per hectare of mpingo which is legally harvestable now with confidence intervals (85% for density, 90% for volume per hectare).

From here we only need to multiply by the total area of Kilwa District under each land cover class, to obtain the expected harvestable stocks in each land cover class. The total number of hectares in the district under Bushland with Emergent Trees is 76,500, so we would expect to find around 10,600 mpingo which are legally harvestable now in that land cover class, although our 80% confidence interval stretches from 757 to 39,400 trees. Full results for all land cover classes containing mpingo in Kilwa District are given in Table 20.

Land cover	Num Harvestable Trees (x 1,000)		Harvestable Volume (x 1,000 m^3)	
1965 Maps				
Forest	3	(0 - 18)	0	(0 - 1)
Scattered Trees	96	(73 - 137)	22	(20 - 26)
Scrub	374	(174 - 704)	173	(115 - 240)
Settlement	20	(2 - 61)	7	(3 - 10)
Thicket	27	(11 - 55)	6	(4 - 8)
Water	5	(0 - 19)	2	(1 - 3)
Woodland	199	(152 - 281)	68	(64 - 80)
1995 LandSat Image				
All Bushed & Wooded Grassland	356	(195 - 605)	96	(68 - 130)
Bushland With Emergent Trees	11	(1 - 39)	2	(1 - 2)
Closed Woodland	65	(26 - 130)	33	(21 - 46)
Cultivated Land	15	(4 - 33)	3	(2 - 5)
General Thicket	7	(3 - 17)	2	(1 - 3)
Open Woodland	322	(253 - 438)	94	(88 - 112)
Woodland With Scattered Cultivation	42	(9 - 133)	7	(4 - 10)

Table 20. Extrapolated number of harvestable trees and total harvestable volume of mpingo which is legally harvestable now with confidence intervals (80% for number of trees, 85% for harvestable volume).

The final task is to sum these results across the land cover classes for each classification, using the Central Limit Theorem to constrain the confidence intervals. In the case of mpingo which is legally harvestable now under the 1995 LandSat classification, we thus obtain an expected number of harvestable trees of 818,000 (80% CI: 634,000 to 1,120,000 trees), while under the 1965 Topographic Maps classification we reach a figure of 724,000 trees (80% CI: 516,000 to 1,107,000 trees). The total expected harvestable volume is 236,000m³ (85% CI: 205,000m³ to 277,000m³) under the 1995 LandSat classification, and 278,000m³ (85% CI: 219,000m³ to 346,000m³) under the 1965 Topographic Maps classification. Results for all models under each land cover classification are set out in Table 21 and Table 22 respectively.

Model	Land Cover Classification: 1965 Maps		Land Cover Classification: 1995 LandSat	
Market Preference	361	(234 - 611)	339	(238 - 521)
Legally Harvestable Now	725	(516 - 1,071)	818	(634 - 1,116)
Potentially Legally Harvestable Later	788	(598 - 1,087)	922	(742 - 1,194)
Illegally Cuttable Now	927	(678 - 1,247)	1,086	(871 - 1,419)
Usable Locally	930	(679 - 1,249)	1,090	(875 - 1,422)
All *	1,286	(1,066 - 1,575)	1,750	(1,478 - 2,096)

Table 21. Expected number of thousands of mpingo in Kilwa District harvestable under different models. 80% Confidence Intervals given in brackets after expected means, (*) except for dummy *All* model where confidence level is 85%.

Model	Land Cover Classification: 1965 Maps		1995 LandSat	
Market Preference	195	(148 - 253)	147	(121 - 180)
Legally Harvestable Now	278	(219 - 346)	236	(205 - 277)
Potentially Legally Harvestable Later	266	(229 - 309)	238	(215 - 267)
Illegally Cuttable Now	294	(246 - 357)	267	(237 - 308)
Usable Locally	294	(246 - 358)	267	(237 - 308)
All	309	(258 - 374)	284	(248 - 328)

Table 22. Expected harvestable volume of mpingo (x 1,000m³) in Kilwa District harvestable under different models. 85% Confidence Intervals given in brackets after expected means.

Comparison of Land Cover Classifications

We are now in a position to estimate the total stocks of the surveyed species in Kilwa District under any given harvesting model. However variation can be expected between the figures calculated according to different land cover classifications[35], and these disparities need to be examined. For this purpose we shall simply examine the total estimated population of each tree species. The results are set out in Table 23.

Comparisons of the figures for the two land cover classification show considerable discrepancy for some species such as mpingo (where the two confidence intervals are almost completely inconsistent), and less for others such as *Bombax rhodognaphalon*. This is not especially surprising given the above noted inconsistency between the two land cover data sources. Those species exhibiting a greater variation in stocks estimate will be those more sensitive to environmental parameters which are distinguished under one classification[36] but not under another. Consistency even varies with model; we saw above that despite the lack of consistency for the *All* model, the estimates thus obtained for mpingo which is harvestable now, are reasonably consistent. It is likely that other land cover classifications would produce different patterns of inconsistency.

Species	Land Cover Classification: 1965 Maps		1995 LandSat	
Dalbergia melanoxylon *	1,286	(1,066 - 1,575)	1,750	(1,478 - 2,096)
Pterocarpus spp.	374	(285 - 508)	510	(387 - 677)
Milicia excelsa	188	(116 - 313)	127	(85 - 210)
Millettia stuhlmanii	1,094	(877 - 1,380)	748	(616 - 923)
Combretum imberbe	189	(87 - 355)	355	(174 - 644)
Afzelia quanzensis	424	(305 - 604)	334	(242 - 473)
Bombax rhodognaphalon	147	(100 - 228)	133	(90 - 196)

Table 23. Estimated populations in thousands of timber trees with DBH exceeding 25cm (* 20cm for *D. melanoxylon*) in Kilwa District. 85% Confidence Intervals given in brackets after expected means.

It is thus probable that the choice of which land cover classification to prefer (as producing the most accurate stocks estimate) varies from species to species. Without any evidence to favour one classification over another the only sensible solution is to take the average of the two figures as our

[35] On just surface area alone the 1965 Topographic Maps apparently report a surface area for Kilwa District 2.5% larger than that obtained from the 1995 LandSat Image.

[36] And by the habitat to land-use mappings that were chosen.

point estimate. When reporting confidence intervals we will follow the precautionary principle and list the more extreme figures in each case (so that the two boundaries will almost always stem from different classifications).

Total Stocks in Kilwa District

The District's stocks for each harvesting model are presented below on a species-by-species basis. They are expressed in terms of the expected number of harvestable trees and the total expected harvestable volume, along with confidence intervals for both figures. The confidence level on the number of harvestable trees is 80%, except for the dummy *All Trees* harvesting model for which the confidence level is 85%. The confidence level on the figures for harvestable volume is 85% in all cases.

Dalbergia melanoxylon

Results for mpingo are presented in Table 24. We estimate the total population of trees (with DBH ≥ 20cm) to be somewhere between one and two million trees, but the number of legally harvestable trees is roughly half that, representing a legally harvestable volume of a quarter of a million cubic metres of mpingo timber. The number of trees with dimensions at market preference is half that still, although there is only a one-third further reduction in harvestable volume as there are still many large trees remaining in more isolated locations. As the data for trees smaller than 20cm DBH was discarded the surveying methodology was not capable of differentiating between the requirements for the *Illegally Cuttable Now* and the *Usable Locally* models, hence their almost identical results. The small apparent increase in harvestable volume from the *Potentially Legally Harvestable Later* model to the *Legally Harvestable Now* model is a data anomaly which should be ignored – the difference is well within the reported confidence limits for both models.

Model	Num Harvestable Trees (x 1,000)		Harvestable Volume (x 1,000 m^3)	
Market Preference	350	(234 - 611)	171	(121 - 253)
Legally Harvestable Now	771	(516 - 1,116)	257	(205 - 346)
Potentially Legally Harvestable Later	855	(598 - 1,194)	252	(215 - 309)
Illegally Cuttable Now	1,006	(678 - 1,419)	281	(237 - 357)
Usable Locally	1,010	(679 - 1,422)	281	(237 - 358)
All	1,518	(1,066 - 2,096)	296	(248 - 374)

Table 24. Total expected number of harvestable trees and total expected harvestable volume of mpingo in Kilwa District harvestable under different models, with confidence intervals (see note above).

Pterocarpus spp.

Results for *Pterocarpus spp.* are presented in Table 25. We estimate the total population of trees (with DBH ≥ 25cm) to be around 440,000 trees, but the number of legally harvestable trees is roughly one third of that with a volume of nearly 200,000m^3. The number of trees with dimensions at market preference is much smaller still at roughly one sixth of the legally harvestable figure, although the further reduction in harvestable volume is less than 50% to just over 100,000m^3. Unlike the case of mpingo, the surveying methodology should have been capable of differentiating between the requirements for the *Illegally Cuttable Now* and the *Usable Locally* models, but the results are again identical, and not much larger than the legally harvestable volume. We anticipate that many of the smaller trees will be harvested before they reach legally harvestable size, for example use for use by local carpenters, or to make ramps for loading logs onto trucks. By number most of the *Pterocarpus* seen were *P. angolensis*, but the biggest ones were mostly *P. holtzii*.

Model	Num Harvestable Trees (x 1,000)		Harvestable Volume (x 1,000 m^3)	
Market Preference	28	(8 - 122)	109	(32 - 262)
Legally Harvestable Now	151	(83 - 280)	197	(109 - 415)
Potentially Legally Harvestable Later	412	(262 - 652)	261	(179 - 394)
Illegally Cuttable Now	422	(263 - 660)	262	(179 - 474)
Usable Locally	422	(263 - 660)	262	(179 - 474)
All	442	(285 - 677)	262	(179 - 476)

Table 25. Total expected number of harvestable trees and total expected harvestable volume of *Pterocarpus spp.* in Kilwa District harvestable under different models, with confidence intervals (see note above).

Milicia excelsa

Results for *Milicia excelsa* are presented in Table 26. We estimate the total population of trees (with DBH ≥ 25cm) to be around 160,000 trees, but the number of legally harvestable trees is only 10% of that, with a volume of 70,000m³. The identical results for the *Legally Harvestable Now* and *Market Preference* models is partly an artefact of the data with relatively few large trees having been surveyed, and partly due to the similar definitions which differ only in straight length requirement (2.5m compared to 3.66m). Some 90% of trees satisfied the straight length requirements as tested by the *Potentially Legally Harvestable Later* model. The results are surprisingly high given the perception of the field team that stocks of *Milicia* are limited and consist of a low number of isolated trees in more densely forested areas. These figures must be interpreted with caution however, as only 36 trees were surveyed to obtain the projections.

Model	Num Harvestable Trees (x 1,000)		Harvestable Volume (x 1,000 m^3)	
Market Preference	16	(4 - 68)	70	(41 - 122)
Legally Harvestable Now	16	(4 - 68)	70	(42 - 123)
Potentially Legally Harvestable Later	142	(77 - 283)	148	(88 - 241)
Illegally Cuttable Now	150	(81 - 310)	148	(88 - 255)
Usable Locally	84	(40 - 239)	137	(80 - 230)
All	158	(85 - 313)	148	(88 - 256)

Table 26. Total expected number of harvestable trees and total expected harvestable volume of *Milicia excelsa* in Kilwa District harvestable under different models, with confidence intervals (see note above).

Millettia stuhlmanii

Results for *Millettia stuhlmanii* are presented in Table 27. We estimate the total population of trees (with DBH ≥ 25cm) to be around 920,000 trees, but the proportion of legally harvestable trees is tiny at just over 1%, with a volume of just 11,000m³. The number of surveyed trees (277) is sufficiently large to suggest this is not just an artefact of the data, although it surprised the field team whose perception was that there are many harvestable trees. This low proportion can probably be attributed to the large size required by loggers who are harvesting for export, and the trees' resultant population structure. There are many more trees available to users with less demanding requirements (around a quarter of a million cubic metres), for example for local use as live fencing, and considerable potential for regeneration if logging pressure is lowered (see *Potentially Legally Harvestable Later* model). However, as the timber is used for flooring, there is no minimum harvestable diameter given in the licensing regulations and there is substantial felling activity in the field it is likely that the diameter of trees felled will decrease substantially in the coming years as the small stock of larger trees is exhausted.

Model	Num Harvestable Trees (x 1,000)		Harvestable Volume (x 1,000 m^3)	
Market Preference	7	(2 - 39)	11	(8 - 15)
Legally Harvestable Now	11	(3 - 42)	14	(9 - 19)
Potentially Legally Harvestable Later	487	(305 - 823)	207	(153 - 273)
Usable Locally	715	(439 - 1,236)	252	(181 - 350)
All	921	(616 - 1,380)	260	(186 - 363)

Table 27. Total expected number of harvestable trees and total expected harvestable volume of *Millettia stuhlmanii* in Kilwa District harvestable under different models, with confidence intervals (see note above).

Combretum imberbe

Results for *Combretum imberbe* are presented in Table 28. We estimate the total population of trees (with DBH ≥ 25cm) to be around 270,000 trees, but only around 2,000 of those trees meet the current market preference dimensions, totalling a volume of just 1,000m³. This is a very low figure given the current rate of harvesting evident in the field, and the few sites in which the species is known to grow. It is likely that even this figure of 2,000 trees is an over-estimate attributable to the land cover classes used, as from field experience the species has very tight habitat requirements (seasonally inundated bare ground). However, the legal minimum size is just 24cm, which is very low for a tree that grows quite large, so it is anticipated that the smaller legally harvestable trees will soon be felled. Including these smaller trees the currently available volume is estimated to be 65,000m³, although this figure does not seem to reflect the observed habitat specificity. These estimates and conclusions must be used with caution as only 20 trees were surveyed, and all of these were within 1km on one transect.

Model	Num Harvestable Trees (x 1,000)		Harvestable Volume (x 1,000 m^3)	
Market Preference	2	(0 - 37)	1	(1 - 3)
Legally Harvestable Now *	125	(22 - 466)	65	(26 - 130)
Potentially Legally Harvestable Later *	110	(21 - 372)	57	(28 - 101)
Illegally Cuttable Now	125	(22 - 466)	65	(26 - 130)
Usable Locally	272	(87 - 644)	103	(43 - 208)
All	272	(87 - 644)	103	(43 - 208)

Table 28. Total expected number of harvestable trees and total expected harvestable volume of *Combretum imberbe* in Kilwa District harvestable under different models, with confidence intervals (see note above).
*** See explanation in text below about misleading results for these models.**

Note the jump in the number of trees from *Potentially Legally Harvestable Later* to *Legally Harvestable Now* is an error of the statistical treatment caused by the fact that the diameter component of the *Legally Harvestable Now* model was virtually insignificant compared to the straight length requirement, which is tested separately under the *Potentially Legally Harvestable Later* model. Expected harvestability of surveyed individuals was 27% under the *Legally Harvestable Now* model, and only 1% higher under the *Potentially Legally Harvestable Later* model. Moreover the total expected number of harvestable trees out of the surveyed set was low; between 5 and 6 for both models. Hence the adjustment factor for under-estimation was high, adding on around 40%, except in the case of the *Potentially Legally Harvestable Later* model where this adjustment factor is halved as the model relies only on straight length and not diameter too. Since all figures fall comfortable within the confidence limits, it is probably safest to average the numbers. We will therefore adopt a point estimate of 118,000 harvestable trees, and 61,100m³ harvestable volume in Kilwa District for all three models: *Legally Harvestable Now*, *Potentially Legally Harvestable Later* and *Illegally Cuttable Now*.

Afzelia quanzensis

Results for *Afzelia quanzensis* are presented in Table 29. We estimate the total population (with DBH ≥ 25cm) to be around 380,000 trees, but the number of legally harvestable trees is less than 10% of that (with a harvestable volume of 45,000m³), and the number meeting *Market Preference* standards is less than 5% of the population, as these preferred dimensions are so large (0.55 x 2.1m). Our perception is that there is a healthy population of this species; the tree is capable of setting seed at only half the legal harvestable diameter, while surveying we saw many isolated large trees and did not see evidence of excessive amounts of felling. Currently most harvesting is on a small-scale to meet local demand (as an alternative furniture timber to *Pterocarpus*); although there is renewed interest in its commercial use to make traditional Zanzibari and modern doors it is too dense for most users. Trees meeting market preference requirements nonetheless still represent a harvestable volume of 33,000m³ as the tree can attain a large size. The situation is similar to *Millettia stuhlmanii* in that there is clear potential for the future in the roughly 250,000 trees which are *Potentially Legally Harvestable Later*.

Model	Num Harvestable Trees (x 1,000)		Harvestable Volume (x 1,000 m³)	
Market Preference	16	(6 - 60)	33	(21 - 52)
Legally Harvestable Now	27	(12 - 78)	45	(30 - 70)
Potentially Legally Harvestable Later	254	(147 - 470)	151	(107 - 197)
Illegally Cuttable Now	308	(171 - 577)	165	(114 - 237)
Usable Locally	371	(213 - 602)	166	(115 - 241)
All	379	(242 - 604)	166	(115 - 241)

Table 29. Total expected number of harvestable trees and total expected harvestable volume of *Afzelia quanzensis* in Kilwa District harvestable under different models, with confidence intervals (see note above).

Bombax rhodognaphalon

Results for *Bombax rhodognaphalon* are presented in Table 30. We estimate total population of trees (with DBH ≥ 25cm) to be around 140,000 trees, with the number of legally harvestable trees some 40% of that, having a volume estimated at 319,000m³. Unlike other species the expected harvestable volume hardly declines as the model requirements get stiffer. This is because the survey data set contained mostly very large or rather small trees, and few of moderate size (and *Bombax* has different architecture from many of the other species surveyed as it grows to an enormous height and tends not to branch for the first 10m). Since the total number of observed trees is only 46 this may not be reflective of the population as a whole.

Model	Num Harvestable Trees (x 1,000)		Harvestable Volume (x 1,000 m³)	
Market Preference	55	(22 - 146)	319	(214 - 440)
Legally Harvestable Now	55	(22 - 146)	319	(214 - 440)
Potentially Legally Harvestable Later	130	(75 - 223)	331	(226 - 426)
Illegally Cuttable Now	57	(24 - 152)	320	(215 - 440)
Usable Locally	140	(90 - 228)	331	(226 - 482)
All	140	(90 - 228)	331	(226 - 515)

Table 30. Total expected number of harvestable trees and total expected harvestable volume of *Bombax rhodognaphalon* in Kilwa District harvestable under different models, with confidence intervals (see note above).

Combined Results

Results for all seven species under consideration are summarised in graphical form in Figure 11 and Figure 12.

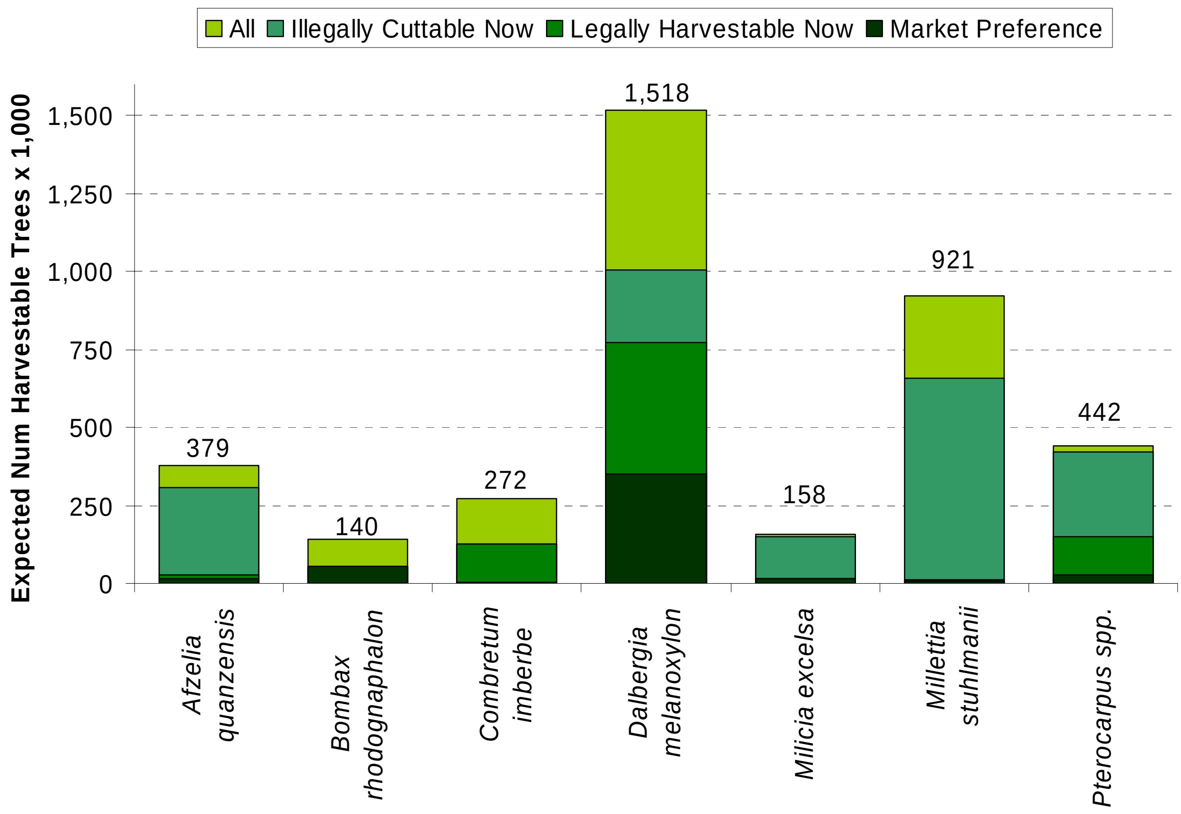

Figure 11. Expected number of harvestable trees in Kilwa District by species under four different harvesting models.

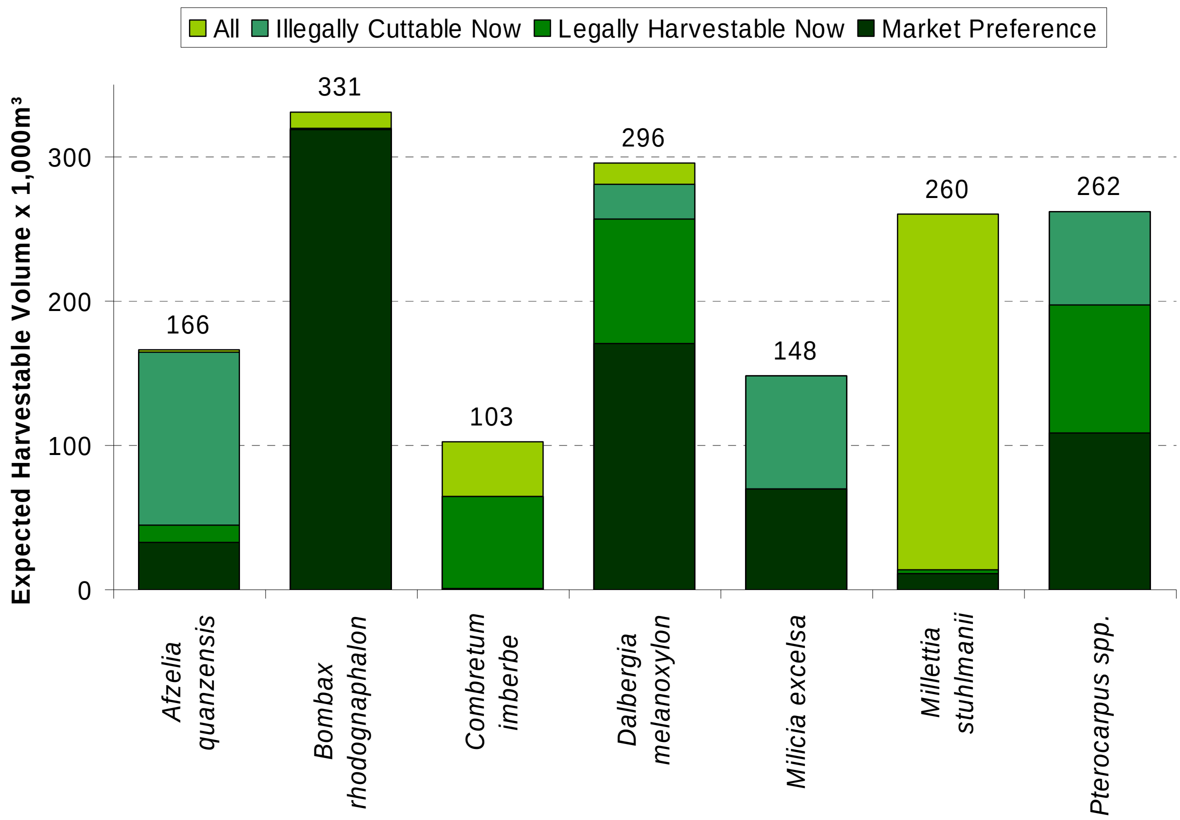

Figure 12. Expected harvestable volume in Kilwa District by species under four different harvesting models.

Discussion

Standing Stocks

Kilwa District still has substantial stocks of timber, see Table 31. Seven species surveyed provided enough data to be analysable. Taken together these species are estimated to be able to yield almost 1 million cubic metres of legally harvestable timber, worth nearly US $50M in licence fees. By volume, mpingo is the most significant of these (at a quarter of a million cubic metres), followed by *Bombax rhodognaphalon*, *Pterocarpus*, *Milicia excelsa* then *Combretum imberbe*[37], each of which are thought to amount to over 50,000m³ of stocks.

Species	Num Harvestable Trees (x 1,000)	Harvestable Volume (x 1,000 m^3)	Licence Value ($k)
Dalbergia melanoxylon	771	257	15,000
Pterocarpus spp.	151	197	11,500
Milicia excelsa	16	70	4,110
Millettia stuhlmanii	11	14	828
Combretum imberbe	118	61	3,580
Afzelia quanzensis	27	45	2,620
Bombax rhodognaphalon	55	319	10,600
TOTAL		**963**	**48,300**

Table 31. Standing stocks of legally harvestable timber in Kilwa District. Licence value (of harvestable volume) computed at 2006 exchange rate of 1,000/- TSh to US $1.

The inventories carried out on behalf of the Forestry and Beekeeping Division (FBD) in 2005 included a total of 21 potentially harvestable forest blocks[38] in Kilwa District, although in some only 4 sample plots were surveyed (Malimbwi *et al.* 2005). They concluded that there are 1.95 million harvestable timber trees in the 342,000ha of harvestable forest in these blocks. This is about double our estimate for the entire district, although they included a much wider range of species, some of which are not currently the subject of commercial exploitation in Kilwa District (District Forestry Office Records 2004)[39]. They calculated a total harvestable volume across all timber species in those forest blocks of 7.6 million cubic metres, which is well in excess of our figures. However this volume equates to a believable average of 3.9m³ per tree, most of which will be species that grow to a large size. By comparison, the average harvestable volume of surveyed species other than mpingo in our study is about 1.8m³ per tree. The difference is attributable to the different use of the term volume: the FBD inventory reports the calculated volume of the whole tree[40], whereas we report only the volume of the main stem (for non-mpingo). We also ignore unharvestable sections of the stem.

Current Harvesting

There is unambiguous evidence in the field of extensive harvesting of all the species surveyed except *Bombax*, so timber stocks must have been substantially larger 5-10 years ago, when we are told increased logging activity began, probably as sources closer to the main market and export point were

[37] Although the stocks estimates for *Combretum* are questionable, see Results chapter.

[38] The surveyed blocks included a mix of Forest Reserves designated for timber production and forested areas of General Land – the legal term for land which is neither privately owned nor reserved by the government.

[39] For example they include *Brachystegia spp.* and *Julbernardia globiflora*, which are only felled in areas closer to Dar that have a severe shortage of hardwood timber (Milledge & Kaale 2005). These two taxa accounted for 40% of their total volume.

[40] They used species specific formulae based on DBH and tree height.

logged out (Milledge & Kaale 2005). Table 32 summarises the timber licences issued in Kilwa District in the four year period running up to the fieldwork.

Species	Licensed Volume (m³)
Dalbergia melanoxylon	490
Pterocarpus spp.	2,846
Milicia excelsa	25
Millettia stuhlmanii	2,168
Combretum imberbe	226
Afzelia quanzensis	526
Bombax rhodognaphalon	54

Table 32. Total harvest licences granted for selected species in Kilwa District, July 2000 to July 2004 inclusive.

The main targets of loggers are currently mpingo, *Pterocarpus* and *Millettia stuhlmanii* in terms both of number of logs being cut and number of stumps seen in the field. We estimate that loggers are willing to drive 5km beyond an existing track to collect logs of these species, and new logging tracks are widespread. Loggers will also come a long way from elsewhere in Tanzania to log in Kilwa District; one group we met had travelled over 800km from Iringa.

What is interesting is that these three species are harvested to meet very different markets; mpingo logging in Kilwa is almost exclusively used to produce billets to export for the music industry, whereas *Pterocarpus* is felled and pit-sawn in the bush to meet domestic demand for furniture and *Millettia* harvested in Kilwa is exported for flooring. We will consider the harvesting of these three species in more detail, and the ecological implications of the felling.

Mpingo

Mpingo is the most numerous timber tree (roughly 770,000 legally harvestable trees) and, despite its relatively small stature (it is the smallest of the surveyed species), still accounts for the second highest volume of available timber. As the number of trees surveyed as the basis of this model was large (608) the 85% confidence interval for the volume available is quite narrow at 205,000-346,000m³. At present the main logging company working in the district is taking large specimens, at least 0.35 x 1.2m, which is the basis of our *Market Preference* model. Some parts of the district, notably around Migeregere village, now have no more trees with these dimensions, but in remoter areas individuals remain with a DBH of 1.3m or more. Local utilization, for example in making utensils, pestles and in construction, is very minor compared with the volume commercially harvested. While surveying we saw that trees down to a diameter of 0.11m are occasionally felled using an axe. Such use though will have a small impact on the future volume of commercially harvestable timber.

Between August 2000 and July 2004 (the only data readily available), 490m³ of mpingo timber was licensed to be harvested (District Forestry Office Records, 2004). This very low rate can clearly be supported. However if, as is suggested by Milledge and Elibariki (2005), only 4% of timber felled is properly licensed, then the current rate of harvesting is probably still sustainable as current stocks of legally harvestable timber would take 84 years to be exhausted, compared to a rotation time of mpingo in the wild estimated to be 70-100 years (Ball 2004).

The confidence interval on this figure, 67 to 113 years worth of stocks, represents a considerable narrowing of the range calculated by Gregory *et al.* (1999) based on surveys of 150km² of woodland in and around Mitaurure Forest Reserve. They recorded a density of harvestable mpingo of 1.03m³ per hectare in an mpingo rich patch – their study site was deliberately chosen as somewhere with substantial stocks[41] – which is three times the highest density computed for any land cover class in this

[41] It has since been harvested.

study, 0.37m³/ha in *All Bushed & Wooded Grassland*.[42] Gregory *et al.* compared their results with other figures available in the grey literature, and found them much lower than other studies. This much larger study reinforces their conclusions that methodological flaws and small sample sizes compromised that previously available data.

The FBD partial inventory found significant stocks of harvestable mpingo in 11 out of 21 forest blocks[43] at densities ranging from 0.33 stems per hectare in Rungo Forest Reserve to 6 stems per hectare in Kitope FR (Malimbwi *et al.* 2005). The lower end of this range fits with our own survey data which found mpingo at densities up to 2.76 trees per ha in the *All Bushed & Wooded Grassland* land cover class, that covers much of Rungo FR, which is roughly equivalent to 3.9 stems per ha[44]. The peak figure of 6 stems per ha lies outside the 95% confidence interval for number of mpingo stems per ha in our *All Bushed & Wooded Grassland* land cover class. Gregory *et al.* (1999) also reported high densities, but their figures include trees down to 10cm CBH. The FBD inventory teams limited their work to defined forest blocks, which can reasonably be assumed to have higher than average densities of harvestable timber, but verification checks are recommended on the figures for the five forest blocks with mpingo densities of 4 stems per hectare or more. It is possible that the sample plots were located in mpingo-rich patches that are not representation of the entire block to which they belong. For example, much of Kitope FR is the globally threatened coastal forest habitat in which mpingo does not occur.

The FBD inventory reported a total volume of mpingo of 327,000m³ (Malimbwi *et al.* 2005), which is reasonably consistent with our data as they calculated the volume for the entire tree, and a large proportion of mpingo is unusable. However the blocks with especially high volumes (results ranged from 0.7m³/ha in Matandu block to 10m³/ha in the Kiwawa II block) bear further confirmation work if licences or concessions are to be awarded on the basis of inventory data. The weighted mean of just under 2m³/ha is very high, even compared to Gregory *et al.*'s figure.

Pterocarpus and Millettia

The situation for *Pterocarpus* is worrying. As Tanzania becomes more prosperous the demand for *Pterocarpus* is increasing because nationally it is the preferred species for doors, window frames, and furniture. Usually the trees are pit-sawn *in situ* to be transported as planks. The majority of teams felling the tree are small, some consisting of only two loggers, but others are larger. Over the period August 2000-July 2004 a total of 2,846m³ of *Pterocarpus* was licensed to be felled. Using Milledge and Elibariki's adjustment factor to account for the majority of timber being illegally harvested we find the current stocks of legally harvestable timber will last for a mere 11 years! Trees setting seed and producing the next generation of *Pterocarpus* will mostly be unharvestable ones. It seems that in the absence of new protection measures, *Pterocarpus* is destined for commercial extinction in Kilwa District. Many of the largest *Pterocarpus holtzii* are found along water courses where felling is banned, although illegal logging is unfortunately common.

The status of *Millettia* is less clear. There is no legal minimum diameter for felling, which according to local sources began only recently. A probable reason for this, given by local foresters, is that the timber cannot be sawn without modern machinery because it is 'hard and blunts hand saws'. The companies felling the logs are international businesses with access to improved power tools, although felling still seems to be done by hand. Almost all the stumps seen in the field are recent. In some places there are a substantial number of sizable trees still remaining, though curiously this is not reflected in the survey data, which suggests that only 1% of trees are of the dimensions taken by loggers in 2004. Field observations carried out since the survey suggest that the largest trees are mostly now felled and logging interest is turning to smaller stems. In ecological terms this is not too worrying, as most regeneration seems to be from suckers, and the tree can set seed at well below the 0.45m diameter limit used in the *Legally Harvestable Now* model.

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[42] Their harvesting model was similar to the *Legally Harvestable Now* model.

[43] They did not report stocks for species in blocks where they were less common.

[44] Based on our finding of 1.41 stems per tree on average.

However there is a concern that the regrowth might not be so harvestable; if the most harvestable stems are creamed off regeneration will be from less harvestable genetic stock. Also the higher density of regrowth stems is likely to mean that few will grow to harvestable size (Chidumayo 1997). Although it is legal to harvest *Millettia* stems of any diameter, whether the companies will be interested in harvesting smaller stems than they currently do is questionable. It could well be that they simply move on to another area or species. Over the four years to end July 2004, harvesting licences were awarded totalling 2168m³. If, as above, only 4% of the harvest is properly licensed then legally harvestable stocks will be exhausted in 18 years.

We estimated the total population of *Pterocarpus spp.* with DBH above 25cm in Kilwa District to be 442,000 trees. By comparison the FBD inventory team estimated 117,000 individuals of *Pterocarpus* present in 5 forest blocks at an average density of 0.69 trees per hectare[45], and with a total volume of 192,000m³ (Malimbwi *et al.* 2005). This implies these five forest blocks: Mitaurure FR, Ngarama North FR, Kisangi, and two blocks around Nainokwe village contain three quarters or more of the district's total stocks by volume. The inventory did not list any results for *Millettia stuhlmanii*.

Other Species

The predicted exhaustion of stocks of *Pterocarpus* could have implications for other species. From our observations in the field it seems that large teams logging *Pterocarpus* or another common species also sometimes opportunistically take rarer species that are adjacent, for example *Swartzia* and *Afzelia*.

Khaya and *Combretum* are both felled for export. Despite their small stocks (in this assessment only 6 *Khaya* trees, and 20 *Combretum* were surveyed) and limited range[46], and there are still patches of very large specimens. These however are unlikely to last long with the current logging interest. *Combretum* is a small tree with a legally harvestable minimum of only 0.24m. It reproduces from seed and probably sets flowers at below the legal minimum diameter, so is unlikely to be threatened with local extinction. Whether the species will continue to be logged once the largest trees have been felled is questionable, unless there is a specific market for the timber. In contrast *Khaya* is a well-known timber. It does not usually set seed below 0.5m DBH (Plumptre 1995 cited in Sheil, 2000) and the tree can attain a massive stature – specimens exist in the District with a DBH of 2m! For this species logging and habitat degradation could lead to local extinction.

Bombax is another timber species with large specimens still remaining. Its use is quite different from the other species surveyed as it is a Class IV timber, not one used for high class joinery. Instead it is used to make light roof joists, for which long planks are obviously necessary. Although it is anticipated that demand will increase in coming years, current stocks are able to support an substantial increase in the modest demand for licences issued at present.

By comparison the FBD inventory team estimated 40,000 *Milicia excelsa* in one forest block with a total volume of 21,000m³, and 20,000 *Afzelia quanzensis* with a total volume of 40,000m³ in two forest blocks (Malimbwi *et al.* 2005). The FBD report also listed a result (167,000m³) for *Swartzia madagascariensis*, data deficient in our study, which they found in only a single forest block.

Impact of Harvesting

Logging of *Milicia* and *Khaya* from the coastal forest for export is a threat to the habitat's structure and integrity; we saw soil erosion and extensive fire penetration of the forest along logging tracks. Subsequent to opening up of the coastal forest, canopy gaps are colonised by fast-growing, light-demanding species rather than timber species (Mwasumbi *et al.* 2000). Thus the composition of the forest changes and the vegetation becomes less 'foresty'. Coastal forest includes many other species of timber tree, such as *Hymenaea verrucosa*, that, although not currently of commercial interest locally, are likely to in future be targeted by loggers in the absence of protection. Fortunately much of the coastal forest in Kilwa District falls within strictly protected Forest Reserves, and so conservation is simply dependent on this protected status translating into effective enforcement.

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[45] Malimbwi *et al.* (2005) report only stems per ha. We have assumed all *Pterocarpus* are single stemmed.

[46] The FBD partial inventory only reported *Khaya anthotheca* in one forest block (Malimbwi *et al.* 2005).

In contrast, although logging in miombo does open up the canopy and the clearing of logging tracks can cause erosion, the habitat is resilient and most will recover in time. For example much of the District was subject to oil exploration in the 1990s, and though many seismic lines were cleared few of these are now readily visible.

However, contrary to expectations and suggestions by Tanzanian MPs that "Kilwa is becoming a desert", this survey found no evidence that on a District-wide scale overall there is forest degradation. This is likely because the population is growing only slowly (UNPF 1997) and, when the main fieldwork was carried out there was very little charcoal production. That situation is now changing, and we have seen trucks filled with charcoal heading up the B2 road, presumably to Dar es Salaam.

Methodology

Species Selection

The stocks assessment was originally intended to count mpingo solely. However as the focus of the MCP's broader programme expanded to include other valuable timbers, it was also decided to count individuals of most of the commonly harvested commercial species.[47] This undoubtedly made the assessment a more efficient use of resources, but it did complicate the surveying. Mpingo is a reasonably distinctive tree with which all members of the survey team were familiar. Moreover it is sufficiently common that the search image is often reinforced, and so remains in the surveyors' minds while walking the transects.

Other species were both less common and often less distinctive, and as a result we believe the surveyors probably missed more of these than mpingo; surveyors may sometimes simply forget to look for rarer species when in the field. This was reflected in analysis. Nine species is probably about the limit for an assessment such as this, unless the surveyors involved are exceptionally observant and very familiar with the appearance of target species, or are surveying only very distinctive species, and six or seven species is probably a better number. Based on our experiences we would recommend careful selection of any species to be included in any similar study. Both the local logging industry and what timber species are in the field are need to be taken into account, so that important species are not excluded and only species that are reasonably widespread are included.

Transects

Transects have a large advantage over sample plots in that no time is lost, walking from one plot to another. Sample plots also require time to be laid out, although similar care could be taken over transect width. In this case we opted to rely on surveyor estimates of transect width. A real concern over the use of selected transects is a violation of the principles of random sampling. Some bias is removed if the surveyors selecting the transects are not familiar with the terrain in advance. However the high importance attached to logistical issues in selecting transects, which must start and end at a suitable pick-up point, must certainly introduce some biases. Our survey did not penetrate the two least accessible areas of Kilwa District which would have required more than one day to complete a transect. This was not a deliberate decision at the beginning – indeed we had made preparations to survey these areas – but a pragmatic choice towards the end of surveying. While surveying we had seen several logging tracks heading into these remote areas and had spoken to locals who told us that the vegetation was "more of the same" of what we were surveying, and therefore the effort required was judged to be not cost effective. However in taking this decision we have probably followed a similar path to loggers; that is the areas we did not cross have possibly been exploited less than those which we did survey.

Conscious and sub-conscious choosing of an easy route to walk also introduced some bias, for example walking on an established animal path or veering slightly to avoid a thicket patch. Some habitats, such as abandoned fields with *Mucuna gigantea*, are virtually impossible to walk through so were consciously avoided. In these cases the transect was walked around the impenetrable area. This bias is

[47] We excluded *Afrormosia angolensis* because it is difficult to identify in the forest mosaic.

likely to have increased our stock estimates of most species, and of mpingo in particular, as it was most often found in open habitats.

It would be possible to quantify accessibility effects for the most common species by stratifying the stocks estimates by distance from the nearest road. This should be possible by GPS, or even more crudely based on walking time from the start or end of the transect. However much of forests we surveyed were criss-crossed by logging tracks, and we do not believe that distance from the nearest road has much impact on harvesting density in Kilwa District; logging companies are prepared to cut a long track into the bush to collect good timber recommended to them by local labourers. Other areas may differ. Alternatively the stocks estimates could be analysed by distance by road from Dar es Salaam as loggers report that transport costs make up a large proportion of their total costs.

Training & Calibration

Training and calibration is also an extremely important part of the exercise. Many foresters have no experience in estimating tree sizes, and it takes some time to get used to the idea, and then to practice it on different species in different habitats. Actually how much time it saves depends on how easy it is to walk in the habitat, how common are the target species at the required size, and how quickly surveyors are able to produce an estimate. If the survey team is likely to encounter 50+ timber trees on a 2 to 3 hour transect then estimations can save significant time, but at lower frequencies using a tape measure to obtain CBH will not delay the survey team significantly. Approaching the tree and circling it, as would be done if physically measuring it, gives a much more accurate idea of whether a tree is harvestable. Estimating straight length however is recommended for taller species over clinometer-based methods which can be quite fiddly, and hence time consuming. Where most surveyed trees are quite short, with less than 5m of harvestable stem, then measuring the straight length using a 3m bamboo pole marked off at 0.5m intervals has proved to be a good low-tech compromise.

An improved and extended calibration exercise would increase confidence in the results, for example carrying out further calibration work in a very different habitat type, or if calibration had been carried out at the beginning and end of surveying, instead of just once. The correct adjustments for apparent under-estimation of harvestability and harvestable volume for samples in excess of 100 trees is not clear, and since the sample size figures generated from the calibration are a direct function of the size requirements of the model, it is possible that we have confounded the effect of sample size with that of tree size on tree harvestability error. Additionally the degree of uncertainty is derived from the same data set used to calibrate the estimates in the first place. An independent, separate exercise to test this degree of accuracy would be more robust. However the calibration exercise itself requires a significant investment of time and resources, first to set it up, and then to walk surveyors through it, so any gains in confidence must be weighed up against the additional time required.

Harvestability

One key area in which surveyors need to be trained, is in assessing harvestability; surveyors need to understand what flaws will make a stem or section of a stem unusable, and therefore should be excluded from the estimation of straight length. However loggers vary among themselves in their criteria. One respected logger we visited the field with was very conservative about which mpingo trees could be harvested; he viewed as unharvestable any with a dead branch above the harvestable stem section. However, the other loggers and foresters we spoke to disagreed. It could be that some labourers do not harvest any tree that might get rejected on the grounds of quality, whereas others are more confident of being paid by their supervisors for felling lower standard trees. Logging companies probably modify their quality criteria according to customer specifications (carvers are less demanding than instrument makers), so harvestability will also show temporal variability.

The nature of this survey meant that none of those involved have worked as loggers. Although the surveyors went to lengths to understand the logging process before beginning work, this understanding increased as the field work progressed, making the early survey data less reliable than the later data, which we are confident is fairly accurate. By surveying from a distance rather than circling a tree the harvestability is likely to have been overestimated as flaws on the far side of the stem would not have been seen, i.e. maybe the number of trees recorded as unharvestable due to hollows resulting from dead branches (which, for mpingo would be recorded as partially dead) is only half the true figure.

The partially nonsensical results for *Combretum imberbe* highlight some of the problems of the statistical method used to calibrate harvestability, although first and foremost is the limitations of a small sample size for that species. However the statistical analysis used to obtain the adjustment for apparent under-estimation of harvestability is flawed because it confounds the effects of sample size with model threshold. The analysis treats all the trees on the calibration course as being from a single species, and then evaluates the accuracy of the harvestability estimate as the model requirements increase. In this sense it is perfectly valid for assessing the degree of under-estimation of the proportion of trees found which are harvestable. However it does not make allowances for different total sample sizes of trees of different species. For example, the analysis is appropriate in making comparisons between the total number of mpingo observed, and the number which are *Legally Harvestable Now* and those which are *Potentially Legally Harvestable Later*, but it is not valid for computing the likely under-estimation of harvestability of mpingo under the *Legally Harvestable Now* model compared to the likely under-estimation of harvestability of *Milicia excelsa* under the same model because the total sample sizes of observed individuals of the two species is different. Since factors such as tree shape can also play a role, ideally a different calibration exercise should be performed for each species (or group of species with similar growth patterns). However a Monte Carlo simulation of different total sample sizes selected from the existing calibration data would eliminate the confounded variables flaw described here.

Sources of Uncertainty

The statistical analysis highlighted a number of different sources of error. Some are a direct result of the methodology used, and reflect the inherent trade-off of speed and expense against accuracy. In evaluating the methodology we must assess the degree of uncertainty which these methods introduced, and how much each one contributed to the overall uncertainty. These are set out in Table 33 in the case of two species, *Dalbergia melanoxylon* and *Pterocarpus spp.*, under the *Legally Harvestable Now* model.

Source of Error	**Degree of Uncertainty**	
	D. melanoxylon	***Pterocarpus spp.***
GPS precision	← *Negligible*	→
Trees not seen inside transect	← 10%	→
Subjective transect width	← 2.8%	→
Sampling effect (Poisson)	16%	24 – 26% *
Error estimating harvestability	5 – 6% *	12%
Land Cover data source	8%	8%
TOTAL	**39%**	**65%**

Table 33. Degree of uncertainty introduced by elements of methodology in computing number of *Dalbergia melanoxylon* and *Pterocarpus spp.* in Kilwa District which are legally harvestable now.
*** varies by according to which land cover data are used.**

From this we can see that the uncertainty introduced by only estimating transect width is generally low compared to other sources of error. Tree size estimation plays some part, but is responsible for substantially less uncertainty than the sampling effect, and we know from the analysis of the calibration data that this error generally decreased as the sample size increased. Hence the best way to reduce total uncertainty is either to carry out more surveying (i.e. invest more resources in the assessment) and/or find a land cover data set which is both accurate and whose boundaries better reflect the ecological conditions which govern the distribution of target species. This latter issue does not greatly impinge on the number of harvestable trees in these two cases but is much more significant when calculating expected harvestable volumes as shown in Table 34. Note that the error estimating harvestable volume combines the sampling effect and estimation error in one statistic.

Source of Error	**Degree of Uncertainty**	
	D. melanoxylon	***Pterocarpus spp.***
GPS precision	⟵ *Negligible* ⟶	
Trees not seen inside transect	⟵ 10% ⟶	
Subjective transect width	⟵ 2.8% ⟶	
Error estimating HV	7 – 9% *	33 – 38% *
Land Cover data source	13%	54%
TOTAL	**27%**	**78%**

Table 34. Degree of uncertainty introduced by elements of methodology in computing volume of present legal harvestable stocks of *Dalbergia melanoxylon* and *Pterocarpus spp.* in Kilwa District. * varies by according to which land cover data are used.

The probabilistic approach forced on the analysis by the decision to estimate tree dimensions actually helps solve a common problem in surveying whereby the size distribution of sampled trees may not accurately reflect the overall size distribution unless sample sizes are very large. Because we cannot be sure of the exact dimensions of any surveyed tree, it is instead taken as representative of a range of sizes, some of which may be harvestable under a given model. Thus the probabilistic analysis smoothes out data which may otherwise be quite uneven, eliminating many data artefacts. This is particularly important when extrapolating from relatively small sample sites to a much wider study area.

Use of Land Cover Data

One problem with the land cover data that was used in this assessment is that it is old: the topographic maps are based on 1965/6 aerial photographs and the GIS shape files are based on satellite images taken between May 1994 and July 1995 that were ground-truthed in 1995. There have been major changes in land use in some parts of the district, such as the on-going clearance of woodland and coastal forest in the Matumbi Hills in the north for extensive maize cultivation. Elsewhere there is local evidence of deforestation and degradation, for example along the B2 Dar es Salaam to Mtwara road many new stalls have appeared to serve refreshments to travellers. The resultant increase in demand for agricultural produce and charcoal has resulted in a zone of deforestation and degradation caused by frequent burning, which does not show up in analysis of the topographic maps due to insufficient differentiation of habitat types, but can be seen when the LandSat maps are compared with current vegetation. However, elsewhere there has been reforestation as secondary forest and scrub have developed in the former fields of villages abandoned thirty years ago during the Ujamaa period, such as at Nambunju.

The topographic maps used in this assessment unfortunately do not come supplied with an explanation of the classification used, leaving all the interpretation essentially to educated guesses. We used the definition that a habitat with at least 20% canopy cover of single-stemmed native trees over 6m in height is woodland (Mufandaedza 2002, Swift *et al.* 1996), and a canopy cover of over 80% is forest. Defining scrub and its boundaries with thicket and scattered trees was not that easy. A further slight confusion when using these maps is that the scattered trees class is nearly always depicted interspersed with scrub at a ratio of approximately 1 scattered trees symbol per 7 scrub symbols. In some places scattered trees are depicted between scrub and woodland, marking a gradation in tree cover, but for the most part there is no discernable pattern. Although we feel two categories are appropriate, scattered trees where there is 5-20% tree cover, and scrub where the vegetation is mostly multi-stemmed, shorter or more open, whether any distinction was made when the maps were drawn is questionable.

There is a notable lack of natural forest cover on the LandSat maps; the only terrestrial forest in the District is in Mbinga Forest Reserve in the Matumbi Hills of the north. The tall evergreen groundwater and riverine forest along and around the Mavuji River, which has canopy trees over 30m tall and 1.5m in diameter, is shown merely as woodland. This can be partly attributed to the original ground-truthing methodology, which mostly confined itself to surveying along main roads, but is also a limitation of using at a sub-national level data produced for national purposes, and is a problem reported by other researchers (S. Mwansasu *pers. comm.*).

Further difficulties in obtaining accurate habitat data were caused by seasonality. The appearance of almost all habitats in this District is highly seasonal. Most miombo trees are deciduous, or semi-deciduous, coming into leaf at the start of the short rains. Surveying early in the dry season is difficult and dangerous as the vegetation is difficult to penetrate and the ground is not visible. It is also impossible to access remote areas when the ground is still waterlogged, so the extent of seasonal flooding must be guessed from the species readily identifiable during the dry season. Later in the dry season, after burning, the habitat is easy to access and traverse. But interpreting it is fraught with complications, for example, the remnants of woody stems could be thicket, or perhaps bushes or multi-stemmed miombo coppice, and their identity and function in the habitat is difficult to guess. Consequently we believe that thicket is under-recorded in the survey data.

Analysis of selected waypoints showed a similar amount of woody vegetation on the satellite images as is recorded on the topographic maps, and of those waypoints showing substantial change, the majority had a higher basal area of trees than when the topographic maps were made. As a further check of the accuracy of the land cover data, we drove a 200km road transect on the loop from Nangurukuru to Nanjirinji and on to Kiranjeranji. Twenty-three waypoints were made where the vegetation was uniform. These waypoints were photographed, described and the land cover compared against those on the two map sources. Although this a major access route to the centre of the district there was no evidence of deforestation, rather afforestation seems to be happening along this road[48].

As with the previous analysis the land cover recorded showed some consistency with the two data sources. Compared with the 1965 topographic maps, 16 of the waypoints have a similar amount of woody biomass, however the remaining 7 surprisingly all had more forested vegetation than four decades ago. Some of the discrepancy can be attributed to minor errors in the old maps, due to the map-making technology available at that time. For example the southern boundary of the coastal forest near Pindiro Forest Reserve is depicted a couple of hundred metres too far north, and it was clear when ground-truthing the map that the trees present had not grown up in the 40 years since the map was drawn. However, when using these maps for other fieldwork we have found them to be very useful and quite reliable e.g. for topography such as stream locations and contour lines. Depicting this information is likely to have been a bigger priority for the map-makers than accurately recording the vegetation. Our conclusion then is that their habitat data should be used with some caution.

The data from the LandSat images are 10 years old and some of the classification ground-truthing was carried out locally, although not along the route we drove. However, by late 2005, of the 23 waypoints surveyed along the Nangurukuru to Kiranjeranji route, 6 had more woody vegetation, 10 had a similar amount and 7 have less. This is not consistent with the analysis of the topographic map data, and might be attributable to the small sample size. Although the information is more up-to-date than the topographic maps, it is still 10 years out of date and there have been some significant changes in land cover since then. The team who produced the maps had in mind potential end-users when drawing up their classification. Accordingly, their classification has obvious utility for those planning game reserves or commercial farms. However, they probably did not foresee using the files for this purpose and many of their sub-divisions did not prove too helpful for our work. The two land cover sub-types that we were most interested in, open and closed woodland, accounted for large percentages of the total land cover (26 and 20% respectively) and contained over 70% of the timber, but were not further sub-divided, whereas bushland is divided into sub-types that are not useful to us.

The satellite images were not obtained until after the surveying. One consequence is that the habitat descriptions recorded in the field were difficult to classify into the various categories and sub-categories, which are less intuitive than those on the simple topographic maps. Fortunately the digital maps are accompanied with a folder of supporting information including two photographs of each sub-

[48] Probably a result of reduced grazing pressure similar to that deduced by Schwartz and Caro (Schwartz & Caro 2003).

type. These provided good guidance, but in some cases more photographs and textual descriptions would have been helpful. To check our post-hoc classification of descriptions we repeated part of one transect (from Kisangi towards Kikole). This was a highly informative exercise which highlighted the difficulty of categorising vegetation. For example dense vegetation where bamboo (*Oxytenanthera abyssinica*) is the most common species. Bamboo dominated vegetation is explicitly classified as thicket by the team who ground-truthed the satellite images, and such areas are mapped as open woodland on the topographic maps. However in Kilwa District small well-developed bamboo patches are mostly found where the tree canopy cover is 20-40% (open woodland), and with ground flora of very similar composition to that of closed canopy woodland. Thus this habitat could justifiably be classified thicket, open woodland or closed woodland. Bamboo is found in association with mpingo and, where it is particularly dense *Afzelia*, but this could not be reflected in the analysis using the LandSat images as most thicket lacks both bamboo and timber.

When surveying our habitat matrix size understandably was smaller than that used by either of the land cover sources as we did not have the advantage of an aerial view of the landscape. One consequence of this was that we tended to record the vegetation around seasonal water courses as a separate transect segment. These patches form ribbons of dense green vegetation in the landscape that contain a disproportionate amount of timber. This vegetation is quite distinctive, and includes much of the *Afzelia* and *Pterocarpus holtzii* seen, but this could not be reflected in the data analysis, where they were classified as forest (on the 1965 topographic maps) and closed woodland (in the 1995 LandSat images).

Similarly, when surveying on foot we were unable to classify a mosaic habitat as being woodland, bushland or grassland with scattered cropland, but instead divided the transect into separate segments. The agricultural land segments were later classified as LandSat land cover sub-types, for example as mixed cropping. Secondary woodland is often readily identifiable when surveying but in this analysis it became part of the scattered cropland matrix.

Stocks of *Combretum* and *Khaya* are low and inherently limited by these species' tight habitat specificity in this District. Unfortunately this was not discriminated in the land cover classifications used. *Combretum* grows on seasonally inundated open ground that has a high water table whereas *Khaya* grows in dense coastal forest with a high water table. Both species would probably be better analysed using geological or soil GIS. The estimates of *Combretum* stocks obtained here seem very high, from our experience in the field. For example it is very unlikely that there is over 60,000m^3 of legally harvestable timber as we are only aware of two sites in the district in which it grows.

Conclusions

Despite heavy harvesting pressure in recent years, the assessment shows clear evidence that substantial timber stocks remain in Kilwa District. However caution must be applied in interpreting the results, first due to the considerable variation in answers given when using the different land cover data sources, and secondly because of the concerns about recent vegetation changes along the main trunk road to Dar es Salaam and other parts of the district. With the exception of *Millettia Stuhlmanii*, the stocks figures reported are all substantially larger than the survey team expected, and it remains to be seen whether more detailed analysis will lead to significant amendments.

Further analysis, which the Mpingo Conservation Project intends to carry out, should include:

- Sourcing (and assessing) alternative land cover data for the District
- Analysis against geological and soil characteristics
- Exclusion of strictly protected areas
- Adjustments for areas which have undergone substantial land cover change
- More detailed analysis by land cover categories on a species-by-species basis, and compared to known ecological characteristics of the species concerned.
- Monte Carlo simulation of the effect of total sample size on under-estimation of harvestability.

Notwithstanding the reservations about the results obtained, our experience suggests that the methods we employed are well-suited to the task in similar situations. Critical to its successful application is a topography and ground vegetation that permits easy passage on foot. Field workers need to be well trained and significant attention must be paid to calibrating surveyor estimates if exact measurements are not taken. However the land cover (or geological) data used will have the biggest impact on the results. Best results will be obtained if the geographical data is both accurate – i.e. up-to-date, and locally ground-truthed – and classified in a manner which is relevant to the purpose – i.e. classification boundaries reflect ecological characteristics of the surveyed species.

Concerns about accuracy of the figures need to be put into context. Our survey team spent a total of less than 100 man days in the field (counting only trained surveyors), whereas the field team for the FBD partial inventory racked up over 160 man days in the field[49] (Malimbwi *et al.* 2005) covering only one third of the district. Moreover cost constraints on the FBD study limited the numbers of sample plots with the result that queries remain about the results for some forest blocks. Concentrating on targeted forest blocks can realise substantial efficiency savings, but woodlands and forest cover most of Kilwa District, and so the approach is less appropriate. Moreover proper selection of forest blocks itself becomes an important part of the exercise. Some of the forest blocks surveyed by the FBD team had already been harvested, and recent logging has not been confined to these blocks, although this maybe an enforcement failure rather than a planning error. In contrast we focused on fewer, known target species, where the FBD team collected data on a number of currently unexploited species.

We can quantify the efficiency of any survey in terms of effective area assessed per man day in the field. Using the rapid transects described in this study we achieved an efficiency rate of >130km² per man day, compared to <24km² per man day achieved by the FBD inventory team. Our method is thus at least 5 times more cost effective than the sample plot based approach adopted by the FBD team.

[49] The FBD report does not explicitly state man days, however it does report a total of 80 ‘crew days’ in Kilwa, where each crew comprised at least 2 crew leaders (Diploma or Degree holders), and additional supervision is provided by a Forest Officer.

References

Ball, S.M.J. (2003) Exploiting a keystone species: timber vs. ecotourism, *Tabebuia heptaphylla* in the northern Brazilian Pantanal. MSc thesis, CEEC, University of East Anglia, UK.

Ball, S.M.J. (2004) Stocks and exploitation of East African Blackwood: a flagship species for Tanzania's Miombo woodlands? *Oryx* **38**(3): 266-272.

Burgess, N.D., Clarke, G.P. & Rodgers, W.A. (1998) Coastal forests of eastern Africa: status, endemism patterns and their potential causes. *Biological Journal of the Linnean Society* **64**(3): 337-367.

Central Census Office (2004) 2002 Population and Housing Census, Volume IV. District Profile: Kilwa. National Bureau of Statistics, Dar es Salaam, Tanzania.

Chidumayo, E.N. (1997) Miombo Ecology and Management. An Introduction. Stockholm Environment Institute, Stockholm, Sweden.

Gregory, A.-M., Ball, S.M.J. & Eziefula, U.E. (1999) Tanzanian Mpingo 98 Full Report. Mpingo Conservation Project, Fauna & Flora International, Cambridge, UK.

Malimbwi, R.E., Shemwetta, D.T.K., Zahabu, E., Kingazi, S.P., Katani, J.Z. & Silayo, D.A. (2005) Kilwa District Forest Inventory Report. Forestry and Beekeeping Division, Dar es Salaam, Tanzania.

MCP (2006) Background Information on Kilwa District. Mpingo Conservation Project, Tanzania.

Milledge, S.A.H. & Elibariki, R. (2005) The Status of Logging in Southern Tanzania. TRAFFIC East/Southern Africa, Dar Es Salaam, Tanzania.

Milledge, S.A.H. & Kaale, B.K. (2005) Bridging the Gap - linking timber trade with infrastructural development in Southern Tanzania: Baseline data before completion of Mkapa bridge. TRAFFIC East/Southern Africa, Dar Es Salaam, Tanzania.

MNRT (2001) National Forest Programme in Tanzania 2001-2010. Forestry and Beekeeping Division, Ministry of Natural Resources and Tourism, Dar es Salaam, Tanzania.

Mufandaedza, E. (2002) Country paper: Zimbabwe. Paper presented at Workshop on tropical secondary forest Management in Africa: Reality and perspectives, Nairobi, Kenya, CIFOR. http://www.fao.org/documents/show_cdr.asp?url_file=/DOCREP/006/J0628E/J0628E67.htm.

Mwasumbi, L.B., Suleiman, H.O. & Lyaruu, H.V.M. (2000) A Preliminary Biodiversity (Flora) Assessment of Selected Forests of the Rufiji Floodplain. Rufiji Environment Management Project, Dar es Salaam, Tanzania.

Ornis Consult (2002) UTUMI Biodiversity Surveys, Tanzania. Ministry of Foreign Affairs / DANIDA,

Plumptre, A.J. (1995) The importance of "seed trees" for the natural regeneration of selectively logged tropical forest. *Commonwealth Forestry Review* **74**: 253-258.

Schwartz, M.W. & Caro, T.M. (2003) Effect of selective logging on tree and understory regeneration in miombo woodland in western Tanzania. *African Journal of Ecology* **41**: 75-82.

Sheil, D. & van Heist, M. (2000) Ecology forest management. *International Forestry Review* **2**: 261-270.

Swift, D.M., Coughenour, M.B. & Atsedu, M. (1996) Arid and Semi-arid Ecosystems *in* McClanahan, T.R. & Young, T.P. *eds)* East African Ecosystems and Their Conservation. Oxford University Press, Oxford, UK.

UNPF (1997) Lindi Region Socio/Economic Profile. United Nations Population Fund, Dar es Salaam, Tanzania.