Modelling Sustainable Harvesting Levels of Timber in the Zomba Plantation: A Logistic Modelling Approach

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ABSTRACT
A study was conducted to develop an environmentally sound strategy for sustainable harvesting of tree crops of the Zomba Mountain Plantation. Its three objectives were; firstly, to estimate current harvesting rates; secondly, to show how the biomass stock is changing in response to growth rates, harvesting rates and planting rates; and finally, using a mathematical model, to predict sustainable levels of harvesting the tree crops. The study focused on the plateau section of the plantation. Data on planted area (compartments), tree growth, damage and harvesting were collected and analyzed using Linest function in Microsoft Excel software. Results indicate that the total biomass of *Pinus patula, Cupressus lusitanica* and *Pinus taeda* is generally decreasing with time. In other words, the current harvesting effort of about 0.061, representing a present harvesting rate of about 22,800 cubic metres per year is unsustainable. Using the logistic equation, the following maximum sustainable harvesting efforts were computed; 0.064 for *P. patula*, representing a present harvesting rate of about 8,533 cubic metres per year; 0.01 for *C. lusitanica*, representing a haresting rate of about 282 cubic metres per year and 0.004 for *P. taeda* representing a harvesting rate of about 500 cubic metres per year. This gives a maximum sustainable harvesting effort of about 0.033, representing a present harvesting rate of about 9,315 cubic metres per year. Therefore, to ensure sustainability of the plantation, it is recommended that the Forestry Department should restrict harvesting to stands at rotation and thinning ages and that such activities should not exceed an effort of 0.033.

1 INTRODUCTION

The importance of forests in improving human welfare is recognized worldwide. Both natural and artificial forests provide basic human needs such as fuel wood, timber, industrial wood and non-timber products. They also provide employment, income and foreign exchange, hence contributing to social and economic development. Equally important are the environmental benefits of forests. They maintain air, water and soil quality, protect watersheds and contribute to biological diversity by providing habitat for flora and fauna. To ensure sustainability of these benefits, there is a need to determine and use sustainable levels of harvesting the wood from these forests. In this paper, sustainable harvesting levels will mean harvesting rates that do not exceed the amount of biomass the forest is able to produce through growth.

Chipompha et al. (1993) reports that Malawi has a total area of 119,140 km^2 of which about 36,800 km^2 is under forests and woodlands, which are estimated to be disappearing at the rate of 2.8% per annum due to rapid population growth and over-dependence on fuel wood for energy. With dwindling natural forests on customary land, plantations have increasingly become a major source of wood products such as firewood, timber, furniture and fiberboard, and non-wood products such as bush meat and edible fungi. Plantations are those exotic or indigenous tree stands established by planting and/or seeding in the process of afforestation or reforestation. Traditionally,

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plantations in Malawi have been mostly of exotic species.

Most plantations in Malawi are in mountainous areas from which streams flow. Therefore, they are not only of economic value but also play an important role of protecting water catchments. Furthermore, they have an increasingly important role of protecting endangered species of plants and animals. Allied to this is their role in recreation and eco-tourism. As the main source of forest products, there is a concern that some plantations, especially those near urban areas, may be overexploited. One such a plantation is the Zomba Mountain Plantation.

Rapid population growth and overdependence on fuel wood for energy threaten the sustainability of the forests in Malawi including the Zomba Mountain Plantation. Government of Malawi (2000) indicates that over 90% of energy requirements in Malawi are met from fuelwood and charcoal and estimates that the urban area of Zomba alone consumes 37,000 m^3 of fuel wood per year, most of which come from the Zomba Mountain Plantation. The fish processing industry around Lake Chilwa also exerts pressure on the resource. According to Government of Malawi (2000), a substantial amount of wood for processing fish is obtained from government-protected areas including Zomba Mountain Plantation. The plantation is within the urban fringe of Zomba Municipality and close to the prime city (Blantyre). Therefore, more wood processing industries are operating in the plantation for easy access to the markets in these centers. Shaba (1999) indicates that in 1998, ten companies at Zomba plateau collected 23,746 m^3 representing a harvesting rate of about 11.49 $m^3ha^{-1}yr^{-1}$. As a comparison, 5 companies at Viphya collected 42,485 m^3 representing a harvesting rate of about 0.85$m^3ha^{-1}yr^{-1}$ whereas at Dedza and Chongoni plantations, 4 companies collected 18,000 m^3 representing a harvesting rate of about 2.75 $m^3ha^{-1}yr^{-1}$. It should be pointed out that these rates were calculated using the accumulated planted areas. If the bare areas were taken into consideration, the harvesting rates could have been higher than the ones presented here. It must also be noted that these rates vary from year to year depending on demand and availability of wood. Unlike Zomba Mountain, some plantations such as Mulanje, Thuchira and Ngala are far away from the urban areas where wood products are needed most. Shaba (1999) reported that consequently wood is overgrowing in these plantations.

The Zomba Mountain Plantation has been hit by several natural disasters over the years. Reports at the plantations office indicate that in 1995, more than 933 hectares of the forest were destroyed by fire. In 1997, about 292 hectares were estimated to have been destroyed by a cyclone. As of November 1999, there was a need to replant 1,670.2 hectares in areas affected by the above problems and clearfelling. These problems threaten the sustainability of the plantation and may further lead to other negative side effects such as soil erosion, land slides, drying up of the catchment area which supplies water to Zomba Municipality and Lake Chilwa wetland, loss of biodiversity, government revenue and source of energy in terms of fuel wood. Therefore, determining sustainable levels of harvest that can be wisely used under a sustainable management regime would be a positive contribution towards sustainable management of the plantation.

The general objective of the study was to develop an environmentally sound management strategy for harvesting the tree crops of the Zomba Mountain Plantation in a sustainable manner. Specific objectives were to:

i. Estimate the current rate (or range of rates) of harvesting the trees

ii. Show how the biomass stock is changing in response to the growth rates, harvesting rates and planting rates.

iii. Suggest suitable ranges of harvesting rates that will ensure sustainability of the plantation.

The underlying hypothesis for the research is that depleting wood resources at Zomba mountain plantation is largely due to harvesting being done beyond what the plantation is able to produce through growth. In other words, thinning and rotation ages as recommended in the silvicultural guidebook of Malawi are not properly followed. During the study, the following assumptions were made:

- That site factor effects on periodic mean annual increments are negligible.
- That each species is planted at an espacement recommended in the Silvicultural Guidebook of Malawi by the forestry Research Institute of Malawi
- That pruning is done as recommended in the Silvicultural Guidebook of Malawi.

However, these assumptions may underestimate or overestimate the modeling results since the guidebook assumes uniform site factors, which is not usually the case for most plantations including

Zomba. Different site factors result in varied mean annual increments.

In Malawi, the Forestry Research Institute of Malawi (FRIM) has attempted to determine sustainability of forestry resources in the plantations by recommending suitable thinning and clear-felling regimes depending on the growth characteristics of the species. However, there are no prescribed sustainable harvesting levels at least for the Zomba Mountain Plantation. Besides this, it is not within FRIM's mandate to enforce the harvesting regimes. As a result, how accurately the regimes are followed depends on the foresters' efficiency and availability of human and material resources, which in most cases are limited. Hence, it is feared that these regimes are rarely followed. This study furthers FRIM's work on sustainable forest management by attempting to determine maximum sustainable yield (MSY) for the Zomba Mountain Plantation using the recommended harvesting regimes from FRIM's work.

Prabhu (1996) defines sustainable forest management as a set of objectives, activities, and outcomes consistent with maintaining or improving the forest's ecological integrity and contributing to people's well-being both now and in the future. This definition encompasses all forest uses and services. In this study, since the main concern is wood resources, sustainable forest management will be defined as a set of objectives and activities aimed at producing the optimum amount of timber and enforcing a harvesting regime such that an approximate balance can be achieved between growth and amount cut. This entails harvesting the wood at an average rate not exceeding the forests' growth rate. The challenge here is not to stop extraction activities but rather to manage them so that harvesting is done in a planned and controlled manner to ensure sustainability. The aim is to continue harvesting in years to come.

Allied to sustainability is the concept of maximum sustainable yield (MSY), which dates back to the 18$^{\text{th}}$ Century. Its more modern form originated in the 1930s. In the context of plantation forestry, MSY is the maximum biomass that one can remove from a plantation without decreasing the resource level. Bell & Morse (1999) summarize MSY in the following manner: 'Any species each year produces a harvestable surplus and if you take that much and no more, you can go on getting it for ever and ever'. However, this is a difficult thing to do, as it requires that one knows precisely the "harvestable surplus" each year. Rather, for practical purposes MSY will be interpreted to mean a harvesting rate equal to the constant growth rate of the timber growing stock. Despite the criticism by several authors (Clark 1976, Hassan 1999) that MSY leads to depletion of the resource during low natural growth periods we argue that it may conversely lead to underexploitation of the resource during high natural growth periods, which compensates for the overexploitation during the low growth periods. So MSY is still a useful strategy for managing renewable resources such as trees. One can use mathematical models to predict MSY of a plantation.

The concept of maximum sustainable yield is based on the fundamental ecological concept of population growth that incorporates the notion of carrying capacity. It is generally observed that growth rate of any living organism follows a sigmoid curve which increases slowly during the early ages, rapidly during middle ages, then slows again during maturity as the population approaches its carrying capacity, which in the case of trees, is the maximum number of trees or biomass an environment can support. In the 1840s Verhust used this observation to develop a mathematical model called the logistic model. Edwards & Hamson (1989) express this model by the differential equation

$$\frac{dB}{dt} = rB\left[1 - \frac{B}{K}\right] \tag{1}$$

where in the case of this study,

$$\frac{dB}{dt} = \text{rate of change of biomass } (\text{m}^3\text{yr}^{-1}),$$
$$B = \text{total biomass } (\text{m}^3),$$
$$K = \text{the carrying capacity } (\text{m}^3),$$
$$r = \text{proportional growth rate of biomass } (\text{yr}^{-1}),$$

Bio-mathematicians and bio-economists such as Clark (1976) and Murry (1993) have used this model to predict growth and sustainable yield of renewable resources such as fish. In forestry, the logistic model has been used to predict the growth of a forest so that foresters can match harvesting and selling plans against the prediction of growth and thereby conclude whether they are cutting more or less than, or an amount equal to the growth. However, there is scant literature on the use of the logistic model in predicting the sustainable levels of harvesting wood in the plantations. Therefore, this study attempts to use the logistic model to predict maximum sustainable yield (MSY) of a plantation.

When a resource such as trees is being harvested, the rate of change of biomass given in equation (1) is reduced to reflect the harvest. Defining the effort involved in harvesting, E (yr^{-1}), to be the proportion of harvested to total biomass per year transforms equation (1) to:

$$\frac{dB}{dt} = rB\left[1 - \frac{B}{K}\right] - EB \quad (2)$$

which can be re-written as

$$\frac{1}{B}\frac{dB}{dt} = (r - E) - \frac{r}{K}B \quad (3)$$

If the rates of change of biomass and total biomass are known for a period of several years, one can use equations (2) and (3) to estimate the effort, the proportional growth rate of biomass and the carrying capacity and hence, estimate MSY of a plantation.

Most sustainable harvesting models include economic discounting, which generally reduce the rotation period of the tree stands and sustainability levels. Since our study was restricted to productivity of the plantations versus sustainable harvesting levels, economic factors were not considered.

2 MATERIALS AND METHODS

2.1 The study site

The study area of the research is the Zomba Mountain Forest Reserve located on and around the Zomba Mountain in the southern region of Malawi between the latitudes 15° and 16° S and longitudes 35° and 36° E

The reserve covers an area of approximately 8,170 hectares of which the Zomba Mountain Plantation consists of 3,444 hectares planted with exotic species. The plantation consists of two administrative sections; Zomba Plateau, with an area of about 2,067 hectares and Zomba Outer Slopes that covers an area of about 1,377 hectares. The former is covered by the scarp, which rings the plateau while the latter is enclosed by roads and firebreaks and is situated on the southern and eastern sides of the scarp base. The Plateau has Class A type of plantation whereas the Outer Slopes is a Class B plantation. The steeper slopes (in excess of 20 degrees) on the Outer Slopes make harvesting difficult (Forestry Department, 1992), so the bulk of harvesting is done on the Plateau. It is for this reason that, of the two plantations, this study focuses on the Plateau.

For management purposes, the plantations are administered in management units known as compartments, which are further divided into sub-compartments of determined sizes (in hectares). A sub-compartment is described as being an area comprising a more or less homogeneous crop in terms of age, species, composition, and condition. Sub-compartments are sub-divisions of the permanent compartments as delineated on the basic forest map. They are not necessarily permanent units of management, being liable to change with the development of the forest through felling, fire and restocking.

2.2 Derivation of Maximum Sustainable Yield Using the Logistic Model

Maintaining a constant resource level is equivalent to maximizing the stand biomass, so as to maintain a constant stocking. In terms of our model, this means the rate of change of biomass, $\frac{dB}{dt}$,should equal zero. Solving for B in equation (2) under these conditions yields

$$B = K\left[1 - \frac{E}{r}\right] \quad (4)$$

as the steady state of stand biomass, and

$$B_{\text{MSY}} = EK\left[1 - \frac{E}{r}\right] \quad (5)$$

as the maximum sustainable yield (MSY).

It can be seen that if the effort is greater than the proportional growth rate, then in the long run the only realistic steady state will be $B = 0$, which implies depletion of the biomass resource. Therefore, to achieve sustainability and ensure a steady state of the resource, the effort must be less than the proportional growth rate of biomass. Knowing the values of E, r and K permits a determination of the sustainable levels of harvest.

2.3 Estimating Efforts, Carrying Capacity, and Proportional Growth Rate of Biomass.

To estimate the rate of harvesting, it is enough to determine the effort, E. Since the amount of biomass harvested, B_h, is given by a linear model of the form

$$B_h = EB, \quad (6)$$

then E can be estimated by means Linest Function in Microsoft Excel.

To estimate the proportional growth rate of biomass and the carrying capacity, we need to estimate the parameters $(r - E)$ and $-\frac{r}{K}$ from equation (3) first. This equation suggests that a linear model of the form

$$Y = \theta - aB \quad (7)$$

where $Y = \frac{1}{B}\frac{dB}{dt}$, $\theta = r - E$ and $a = \frac{r}{K}$, is expected. Hence, one can use a least squares method to estimate the parameters θ and a. Applying the least squares criterion (Giordano, F. R., 1997) gives

$$a = \frac{1}{\Delta}\left\{\sum_{i=1}^{N} B_i y_i - \sum_{i=1}^{N} B_i \sum_{i=1}^{N} y_i\right\} \tag{8}$$

and

$$\theta = \frac{1}{\Delta}\left\{\sum_{i=1}^{N} B_i^2 \sum_{i=1}^{N} y_i - \sum_{i=1}^{N} B_i \sum_{i=1}^{N} B_i y_i\right\} \tag{9}$$

where N is the number of years for which data is collected, (y_i, B_i) the data points being used for $1 \leq i \leq N$ and $\Delta = N\sum_i B_i^2 - \left(\sum_i B_i\right)^2$.

These computations can be done using `Linest Function` in Microsoft Excel software. Linest is a statistical function that uses least squares method based on equations (8) and (9) to calculate a straight line that best fits a given data set, and returns an array that describes the line.

In this study equations (8) and (9) were used to estimate the parameters, $\theta = r - E$ and $a = r/K$, and hence, to estimate the proportional growth rate of biomass, r, and carrying capacity, K, in order to compute the steady states and maximum sustainable harvesting levels of biomass.

2.4 Data Collection Methods

Data were collected from three main sources; Zomba Plantation Office, Forestry Research Institute of Malawi and Forestry Department Headquarters. Finally a field study was carried out to check species in the compartments that were assumed to have been clear-felled at rotation age. The following is an outline of type of data collected from each source.

2.4.1 Zomba Plantation Office

From Zomba Plantations Office, the following data were collected.

- List of compartments, sub-compartments, their sizes, species and year when planted.
- Amount of biomass harvested in each year from 1992 to 2000 – the years for which data were available. However, within this 9-year period some 5 years had incomplete data. In such cases, harvesting data for these years were extrapolated as follows:

  For each year with complete data, proportion of biomass harvested in each month, say, $P(i, j)$, was computed. Note that $P(i, j)$ denotes the proportion of harvest for year i in month j, where i ranges from 1 to 4, the number of years for which harvesting data were complete and j ranges from 1 to 12, the number of months in a year. For each month, the mean of the proportions, $q(j)$, for different years calculated above was computed. For each year with missing data, the total of the harvests known (B_t) and the sum of $q(j)$'s for the months with data, (q_t), were computed. Therefore, B_t/q_t gave the extrapolated harvest.

  Since harvesting data obtained from the progress reports is the biomass reported to have been supplied to wood processing companies, it excludes a substantial amount of biomass left in the form of branches and end portions of stems, which are normally collected for firewood. Kapila (1989) showed that biomass left in the field in form of branches and end portions of stems account for more than 20% of the total wood harvested at Zomba Mountain Plantation. Therefore, to take this biomass into account, the harvesting data collected was increased by 20%. It was discovered that until 1992, harvesting data from the two administrative sections of the Zomba Mountain Plantation were combined. Therefore, during data analysis, harvesting data for 1992 were not used.

- The areas damaged by fire, cyclone, etc were available in hectares, and (for purposes of this study), were converted to biomass equivalents.

2.4.2 Forestry Research Institute of Malawi (FRIM)

The following data were collected from FRIM:

- Recommended thinning and clear-felling regimes for different species
- The biomass in each compartment in 1992, herein called the 1992 opening biomass, B_{op}. Periodic mean annual increments (PMAI) for different species Periodic mean annual increment (measured in $\mathrm{m}^3\ \mathrm{ha}^{-1}\ \mathrm{yr}^{-1}$) is the average increase in tree size over a period of years (usually 5 - 10 years) derived by dividing total tree size at any point in time by total age (Avery, 1983).

2.4.3 Department of Forestry Headquarters

From the Department of Forestry headquarters, the following data were collected.

- Amount of biomass supplied to different wood processing companies operating at the plantation from 1994-1998.
- Areas damaged by fire from 1994-1999.

3 DATA ANALYSIS

Compartment numbers and their areas, species and planting year, stocking for each species, PMAI, opening biomass for 1992, and area damaged were entered in a Microsoft Excel spreadsheet from which the following were calculated for each compartment in each year.

- Biomass Added (B_a)

  This was calculated from the formula B_a = PMAI × Area × 1 Year. The sum of biomass added in all the compartments in a particular year gave the total biomass added for that year which is equivalent to biomass increment or "harvestable surplus".

- Total Biomass (B)

  This was obtained from the sum of opening biomass and biomass added.

- Ideal Biomass Harvested (B_h)

  This is the biomass which should have been harvested under a 'normal' management regime, hence the word 'ideal'. It was calculated to compare it with the actual biomass harvested. It was assumed that all stands at rotation age (except those that were still standing at the time of the research) and stands at thinning age were clearfelled and thinned, respectively. Therefore, the total biomass of stands at rotation age gave the biomass clearfelled. Biomass thinned was calculated from the formula

  $$\text{Biomass thinned} = \frac{\text{PMAI} \times \text{Stems thinned} \times \text{Age}}{\text{Number of stems before thinning}}$$

- Biomass Damaged (B_d)

  Areas damaged, were converted to their biomass equivalents by using the formula

  $$B_d = \frac{\text{Area damaged}}{\text{Compartment area}} \times B \qquad (10)$$

- Closing Biomass (B_c)

  This is the difference between the total biomass and biomass harvested, thinned or damaged. In other words $B_c = B - B_h - B_d$

  The closing biomass of the i^{th} year is the opening biomass of the $i + 1^{\text{st}}$ year. Thus,

  $B_c^i = B_{\text{op}}^{(i+1)}$, for $i = 1, 2, \ldots, 9$.

- Change in Biomass

  This is the difference between the closing biomass and the opening biomass for each year. So, change $\Delta B = B_c^i - B_{\text{op}}^i$. A negative change indicates that more biomass was harvested and/or damaged than that produced by the plantation in that year (i.e. B_a). For small time intervals, change in biomass can precisely be represented by the rate of change, $\frac{dB}{dt}$. Since our time interval is one year, change in biomass is only an approximate value for this derivative $\frac{dB}{dt}$.

3.1 Estimation of Parameters of the Logistic Equation

E was estimated from (6) while $-r/K$ and $r - E$ were estimated from (8) and (9) respectively. In both cases, the Least Squares method was used.

4 RESULTS AND DISCUSSIONS

Except for actual biomass harvested and increment, the results are presented per species. The actual biomass harvested was not available by species. The species included in the "other" are *Cupressus torulosa, Pinus elliotti, Pinus pseudostrobus, Pinus ponderosa* and *Khaya anthotheca*. The results are presented in three sections; actual harvest versus 'harvestable surplus', change in total biomass with the final section estimating steady states and sustainable harvesting levels.

4.1 A Comparison of Actual Harvest and Harvestable Surplus

Comparison of actual biomass harvested and biomass increment (harvestable surplus) reveals that more wood is being harvested than the forest's growth rate (see Figure 1).

It is apparent from Figure 1 that the general tendency has been to harvest more biomass than the annual increment. This shows that the current harvesting rate, which is about 22,800m^3 per year on average (an effort of 0.061), is not sustainable and may lead to decrease in total biomass in the plantation. From the foregoing discussion on sustainable forest management, it is clear that to ensure sustainability, biomass less than or equal to the increment (harvestable surplus) should have been harvested in each year.

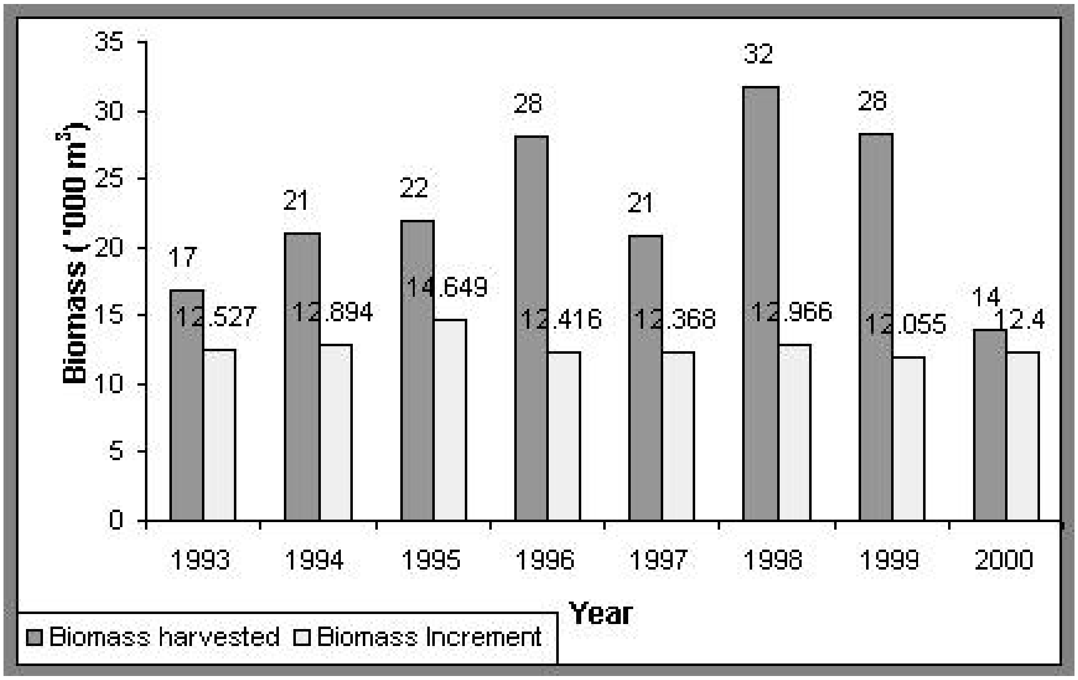

Figure 1: Actual Biomass Harvested Versus Ideal Biomass Increment

Table 1: Trends in Total Biomass (cubic metres)

Year	*P. patula*	*C. lusitanica*	*P. taeda*	Other	Total
1993	279,709	27,616	91,975	21,645	420,945
1994	274,979	27,996	92,786	19,228	414,989
1995	264,730	28,116	94,238	15,642	402,726
1996	214,374	29,390	90,088	16,336	350,187
1997	215,681	30,289	92,328	17,230	355,528
1998	219,912	20,385	94,636	17,925	352,858
1999	219,817	15,509	80,627	18,455	334,408
2000	229,614	15,649	82,537	19,318	347,118

4.2 Trends in Total Biomass

As expected from the unsustainable harvesting, it was found that the total biomass for all species was generally decreasing with time (see Table 1 and Figure 2). Since *P. patula* is the most dominant species in the plantation (with biomass of more than 63% of the total biomass), its change in biomass is more prominent than that for the other species. Therefore, changes in total biomass based on this species will now be fully discussed.

The results for *P. patula* show that there has been a decrease in total biomass since 1993. However, there is a slight increase since 1997. This may suggest that the biomass is cyclic and that it is beginning to increase again. However, to be certain of this cyclic behaviour, one would need to have data sets for relatively longer period of time than that covered by this study.

4.3 Estimation of the Steady States and Sustainable Harvesting Levels

Table 2 below shows the estimated values of the effort (E), proportional growth rate of biomass (r) and carrying capacity (K) for different species as calculated from Appendix 1.

Since effort is defined as the proportion of harvested to total biomass, those listed in Table 2 imply that to achieve sustainability, at most 6.4% of *P. patula*, and 1.0% of *C. lusitanica* and 0.4% of *P. taeda* biomass should be harvested each year. This is appropriate for sustainability purposes because in each case, the proportional harvests (E) are less than the proportional growth rates (r). Any harvest beyond these efforts is unsustainable.

The carrying capacities mean that if all harvesting activities were suspended and proper management practices were followed, then at their rotation ages, the species would, over time, grow to a maximum biomass of about 400,000 cubic metres, 29,000 cubic metres and 131,000 cubic metres, respectively. Substituting values of these parameters in equations (4) and (5) yield maximum sustainable yields (MSY) and the steady states (SS) presented in Table 3 below.

The maximum sustainable yields mean that to ensure sustainability, at most 8,533 cubic metres of *P. Patula*, 282 cubic metres of *C. lusitanica* and 500 cubic metres of *P. taeda* must be harvested each year. Thus, the total sustainable harvest for the plantation appear to be 9,315 cubic

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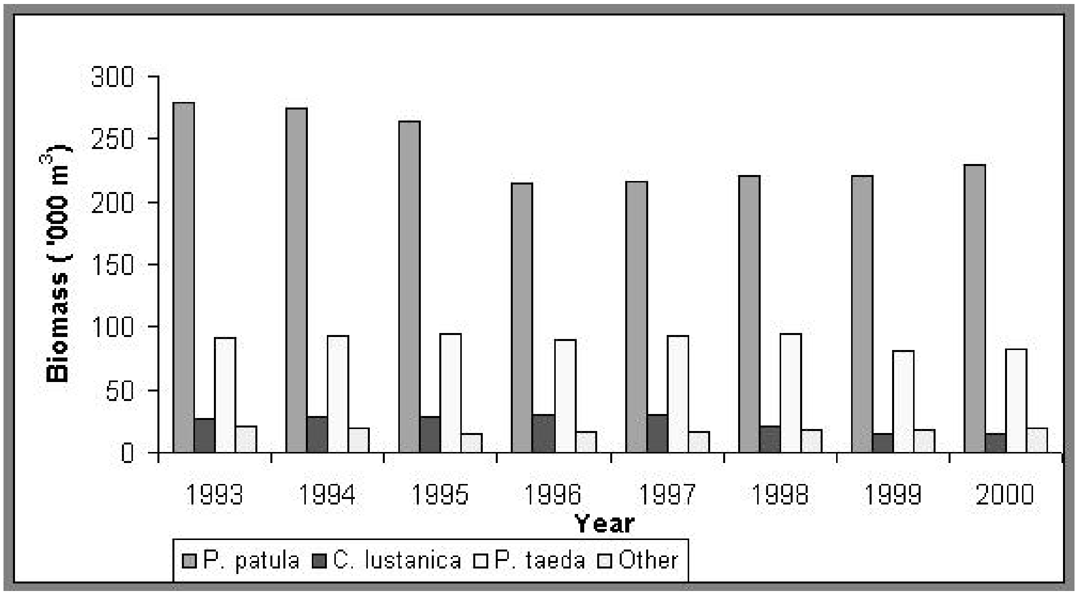

Figure 2: Trends in Total Biomass (cubic metres)

Table 2: Estimates of Efforts, Proportional Growth Rates and Carrying Capacities for Different Species.

Parameter	Value for P. patula	Value for C. lusitanica	Value for P. taeda
Effort (E)	0.064	0.01	0.004
Growth Rate (r)	0.096	0.358	0.0.069
Carrying Capacity (K)	400,000	29,000	131,000

metres per year. The steady states mean that if the sustainable harvesting levels are used followed by immediate replanting of the felled areas, then in the long run there will be a constant resource level of about 28,400 cubic metres given by the sum of these steady states.

Taking the total biomass to be the sum of individual steady states, this harvest is equivalent to felling about 25 hectares of 30-year-old *P. patula* stands every year and represents an effort of about 0.033. It must be pointed out that these sustainable harvests include wood left in the field in form of branches and end portions, which, according to Kapila (1989), constitutes about 20% of the total harvest. Therefore, the realistic sustainable harvest is 80% of the levels suggested in this study.

It must be borne in mind that the sustainable harvesting levels were arrived at by using the logistic equation and from the assumptions indicated in the introduction. In practice, however, silvicultural operations such as pruning are untimely or not followed at all. This nullifies any potential to be realized from such operations. In reality, periodic mean annual increments are affected by site factors like soil fertility and moisture. Moreover, the accuracy of actual biomass harvested depends on the forest assistants' efficiency in estimating standing biomass and recording the exact biomass harvested per compartment and species. Also, in trend studies data taken over a long period of time are needed in order to make better predictions. In our case, data were available for a period of nine years only.

Table 3: Maximum Sustainable Yields (MSY) and Steady States (SS) for *P. patula*, *C. lusitanica* and *P. taeda* at Zomba Plateau

Species	MSY (m^3)	SS (m^3)
P. patula	8,533	133,333
C. lusitanica	282	28,211
P. taeda	500	122,840

These limiting factors may have resulted in overestimation or underestimation of the total biomass, rates of change of biomass and, hence, overestimation or underestimation of the sustainable harvesting rates. Nonetheless, the results in this study give a general picture of how the forest is changing and are therefore, important for management purposes.

5 CONCLUSIONS AND RECOMMENDATIONS

The scarcity of data and poor recording and keeping of data by Forest Assistants are some of the limitations of this study. If data were available per species for, say, the past 30 years, then one would be able to determine trends in total biomass and make better predictions of rates of change of biomass and sustainable harvesting levels. Nevertheless, the following major conclusions can be deduced from the results of the study.

- The current harvesting effort of about 0.061 is not sustainable for the plateau section of the Zomba Mountain Plantation and hence
- Harvesting efforts of about 0.033 appear to be sustainable for the plateau plantation.

In view of the above conclusions and to ensure sustainability, we recommend that harvesting should be restricted to stands at rotation and thinning ages and that it should not exceed 3.3%.

Apart from the above recommendation, the following should be done to reduce limitations of future studies on sustainable forest management.

- Progress reports should be compiled by compartments and species.
- Improved data storage techniques such as use of computers should be adopted at the plantation and Forestry Department headquarters as opposed to current hard-copy system which is liable to damage.
- Forest assistants at the plantation should be equipped with forest management skills such as data collection and record keeping.

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