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CONSERVATION

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**Modelling Tree Growth to Determine the Sustainability of
Current Off-take from Miombo Woodland: a case study from
rural villages in Malawi.**

Journal:	<i>Environmental Conservation</i>
Manuscript ID	EC-16-08-198.R1
Manuscript Type:	Research Paper
Date Submitted by the Author:	n/a
Complete List of Authors:	Green, Emma; University of Southampton, Centre for Environmental Sciences Eigenbrod, Felix; University of Southampton, Centre for Biological Sciences Schreckenber, K; Southampton University, Centre for Environmental Sciences Willcock, Simon; University of Southampton, Centre for Biological Sciences; Scotland's Rural College; Bangor University, School of Environment, Natural Resources and Geography
Keywords:	Africa, ecosystem service, forest, modelling, sustainable forest management, yield, Zomba
Note: The following files were submitted by the author for peer review, but marked to be sent in Off-Line.	
Title Page - not for the attention of reviewers	

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Title: Modelling Tree Growth to Determine the Sustainability of Current Off-take from
Miombo Woodland: a case study from rural villages in Malawi.

Running Head: Modelling Tree Growth in Malawi

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Key words: Africa; ecosystem service; forest; modelling; sustainable forest
management; yield; Zomba

Abstract

Miombo woodlands supply ecosystem services to support livelihoods in southern Africa. However, rapid deforestation has necessitated greater knowledge and understanding of tree growth and off-take rates. We established 48 tree inventory plots within four villages in southern Malawi, interviewed representatives in these same villages about tree management practices, and investigated the impact of climate on vegetation dynamics in the region using the ecosystem modelling framework LPJ-GUESS. Combining our data with the forest yield model MYRLIN revealed considerable variation in growth rates across different land uses; forested lands showed the highest growth rates (1639 [1594-1684] kg ha⁻¹ yr⁻¹), followed by settlement areas (1453 [1376-1530] kg ha⁻¹ yr⁻¹). Based on the modelled MYRLIN results, we found that 50% of the villages had insufficient growth rates to meet estimated off-take. Furthermore, the results from LPJ-GUESS indicated that sustainable off-take approaches zero in drought years. Local people have recognised the unsustainable use of natural resources and have begun planting activities to ensure ecosystem services derived from miombo woodlands are available for future generations. Future models should incorporate the impacts of human disturbance and climatic variation on vegetation dynamics; such models should be used to support the development and implementation of sustainable forest management.

Introduction

Forest growth models have been applied to diverse forest types and have demonstrated their suitability in northern latitudes, tropical moist forests and plantations; however, application in Africa and in indigenous forests is limited (Saint-Andre *et al.* 2003; Malhi *et al.* 2014). To facilitate sustainable use of forest resources, decision makers require

50 knowledge of the current forest condition and predictions of the future state of forests
51 (Phillips *et al.* 2003). However, in the absence of long-term tree inventory data, often
52 unavailable in developing countries partly due to economic and time constraints
53 (Grainger 2008), forest growth models are useful for assessing the current and future
54 growth rates of trees, and therefore are crucial for informing sustainable management
55 (Vanclay 2003).

56

57 Miombo woodland, dominated by the genera *Brachystegia*, *Julbernardia* and *Isoberlinia*
58 of the family Fabaceae, is the most extensive dry forest and tropical seasonal woodland
59 in central and southern Africa, covering around 2.4 million km² (Deweese *et al.* 2010).
60 Approximately 75 million people inhabit miombo woodland regions, with a further 25
61 million urban dwellers reliant on provisioning ecosystem services derived from
62 miombo woodland, e.g. timber and charcoal (Deweese *et al.* 2010). However, the majority
63 of miombo woodland across Africa is in decline, mainly driven by conversion to
64 agricultural land and extraction of wood for energy (Willcock *et al.* 2016). Additionally,
65 increases in temperature and reductions in moisture availability due to climate change
66 are expected to result in accumulation of C4 grasses and increased fire frequency,
67 adversely affecting the productivity of miombo woodland (Lehmann *et al.* 2014), which
68 may have concomitant negative impacts on human wellbeing (Fisher *et al.* 2010).

69

70 The aim of this study is to present a new rapid assessment approach for first-order
71 estimation of the sustainability of forest off-take rates in a region where long-term tree
72 inventory datasets generally do not exist, namely the data-deficient miombo woodlands
73 of Malawi. Our approach involves combining quantitative sampling of the current
74 woody biomass with remotely sensed globally available land cover data (GlobCover),

and then using two freely available forest growth models (MYRLIN and LPJ-GUESS) to estimate current and potential future above-ground growth rates. We compare these modelled results with the perceived sustainability of current off-take rates which we quantify based on interviews with local informants.

Methodology

Study area

The study was conducted in four villages located in the districts of Zomba and Machinga (southern Malawi). The villages were selected as part of the ESPA ASSETS project (<http://espa-assets.org/>) and are located on a transect between Lake Chilwa and the Zomba-Malosa Forest Reserve (Fig. 1; Appendix S1).

Inventory methods

In June and July 2013, three 20 x 20 m sample plots were established within each dominant land use (forest [predominantly miombo woodland], settlement, cropland and grassland) of the four study villages using a random stratified sampling strategy (see Appendix S1), resulting in 48 plots in total. Within plots, the diameter at breast height outside bark (DBH; 1.3 m) of living woody flora >0.5 cm DBH was measured to the nearest millimetre using a calliper or diameter tape, in accordance with the RAINFOR methodology (Phillips et al., 2009). Species position was recorded using a Global Positioning System (Garmin GPSmap 60CSx). Banana and bamboo species were excluded from this study due to classification as a perennial crop or grass. The vernacular name (in Chichewa or Yao) and growth rate category

(fast/medium/slow/unknown) of a species was provided by a local expert (Appendices S1 and S2).

Interviews

Semi-structured interviews were carried out with the village headman, accompanied by the VNRMC member in each of the four villages (8 people in total). Interviewees were asked about harvesting practices and also to estimate the time period for which they considered the tree resources within the villages would remain intact, to establish local perceptions of sustainability. Specific interview questions included:

- Where do villagers obtain timber, woodfuel and poles from within the village?
- How much of each tree is utilised for timber, woodfuel and poles?
- How long do you expect the village forest to last?
- How long would you like the village forest to last?

Modelling Tree Growth

We selected two contrasting models requiring minimum primary input data, advantageous for application in data deficient regions: 1) Methods of Yield Regulation with Limited Information (MYRLIN), a growth and yield model aimed at organisations with limited information on forest dynamics (Alder *et al.* 2002); 2) The Lund-Potsdam-Jena generalized ecosystem modelling framework (LPJ-GUESS), a forest process model that combines the dynamic vegetation model LPJ DGVM, with the forest gap model FORSKA (Smith *et al.* 2001; Sitch *et al.* 2003).

MYRLIN

MYRLIN was used in this study to model current above-ground biomass (AGB) growth rates within land use categories. It assumes that the pattern of diameter increment of tropical trees is similar, allowing predictions to be made about tree growth rates (Vanclay 2003). Species were grouped by growth rate (fast/medium/slow/unknown) for simulation of the mean diameter increment (Dinc) (cm year^{-1}) for each land-use category within the four villages, producing village specific Dinc values (Appendix S2, Appendix S3). To produce more generic, study area estimates, the data from the four villages were combined to create an overall mean Dinc for each land use, weighted by the number of trees present in the given land use (Fig. S3.1, Step 1). The overall mean Dinc values were calculated using Microsoft Excel 2007 and IBM SPSS Statistics 21.

To calculate the sustainability of current annual tree off-take (kg per capita), the Dinc (cm yr^{-1}) required conversion to AGB growth ($\text{kg ha}^{-1} \text{yr}^{-1}$). AGB growth was estimated using the tropical dry forest, excluding tree height, allometric model of Chave *et al.* (2005). Due to lack of species specific wood density data, often only available for a proportion of species in an inventory plot (Flores & Coomes 2011), the mean value for African species from a global tropical forest database of 16,468 records (0.6047g cm^{-3}) was used (Zanne *et al.* 2009; Chave *et al.* 2009).

The estimated AGB growth was calculated by subtracting the measured biomass (based upon DBH only) from the modelled annual biomass increase (DBH + Dinc) in the plot (Fig. S3.2, Step 3). This was then multiplied by the number of trees in a given plot, converted to $\text{kg ha}^{-1} \text{yr}^{-1}$ and a 95% confidence interval (CI) was calculated for the mean

AGB growth per land use type. Therefore, our CI addresses plot natural variability and sampling error in estimating biomass growth, but ignores the unknown modelling error within MYRLIN. The latter is beyond the scope of this investigation, but has been reported elsewhere (Vanclay 2003; Smith *et al.* 2001).

Estimation of land use area

To estimate the sustainable offtake at a village level from MYRLIN, the means of the plot-scale estimates were multiplied by the available area of the relevant land cover. The area of forest, grassland and cropland in each village were derived from the Globcover 2009 land cover map (European Space Agency 2010). Globcover does not provide the area of settlement therefore this was calculated by measuring the area of 100 randomly selected homesteads (defined as the area of land including and immediately surrounding houses) in each village using ArcMap10.1 software. The mean area of homesteads was multiplied by the number of houses present in the village to obtain a settlement value (Appendix S4; MASDAP 2013). This was removed proportionally from the other land cover areas. The model-derived AGB growth was multiplied by the area of the respective land use in each village to gain a village level estimation.

LPJ-GUESS

LPJ-GUESS is used to simulate natural vegetation dynamics in response to inter-annual climatic variations, in the absence of human interference (Smith *et al.* 2001). It has been

applied in a number of studies estimating vegetation dynamics and carbon exchanges at regional and local scales (e.g. Morales *et al.* 2007). LPJ-GUESS was utilised in this study to investigate the degree to which climatic variables affected tree growth rates within the study area to establish the sensitivity of off-take rates to climate change. The annual biomass growth data was simulated for the period 1995 - 2005 at a resolution of 0.5 degree latitude x 0.5 degree longitude; resulting in two cells of interest, with three of the study villages in one cell and the fourth study village in the other. Data input included precipitation, temperature, solar radiation, soil data and atmospheric carbon dioxide concentration, obtained from the Climate Research Unit Time Series 3.0 data set (Harris *et al.* 2014). The model yields information on the carbon biomass, including roots (estimated to contribute 25% to AGB (Lewis *et al.* 2009)). Carbon biomass is assumed to be 50% of dry biomass (Chave *et al.* 2005).

Results

Above-ground biomass growth within the study area

The 48 plots sampled contained 909 stems from 118 species (Appendix S2), indicating large diversity in tree species. Trees in forest areas displayed the smallest DBH (mean 6.5 [95% C.I 5.55-7.53] cm) values in comparison with grassland (8.61 [5.39-11.82] cm), settlement (15.18 [12.95-17.41] cm) and cropland (27.98 [20.62-35.33] cm), respectively. Tree growth was dominated by trees less than 5 cm DBH in most plots in all land use categories.

Using MYRLIN, the estimated AGB growth was variable across the study area (Fig. 3) and between land uses within villages (Fig. 4). The largest AGB growth, and thus the

largest sustainable yield, within the study area was found in the forest land use category (1639 [1594-1684] kg ha⁻¹ yr⁻¹), followed by a settlement area (1453 [1376-1530] kg ha⁻¹ yr⁻¹). Cropland and grassland displayed the lowest annual AGB increase per unit area in all villages. The largest AGB growth within villages was found in the forest land use in Village 4 (4913 [4821-5006] kg ha⁻¹ yr⁻¹; Fig. 4). The settlement land use category in Village 3 had the second largest AGB growth per hectare (2419.08 [2230-2608] kg ha⁻¹ yr⁻¹).

The AGB biomass modelled using LPJ-GUESS (1995-2005) varied temporally between the Zomba and Machinga Districts. This was subsequently reflected in the annual change in AGB (Table 2). Both districts displayed large climate-driven decreases in AGB in specific years; the Zomba District displayed large decreases in 2000, 2004 and 2005, whilst Machinga District displayed large decreases in 1997, 2000 and 2003.

Off-take rates

Using local government data to estimate the mean annual consumption of wood (off-take rate = 570.51 kg per person (Government of Malawi 2010; Appendix S5) and assuming that the annual sustainable harvest rate of the modelled AGB growth for the individual villages was 80% (Appendix S6), shows that Village 1 and 4 are currently harvesting wood within sustainable limits, while Villages 2 and 3 have annual deficits of 187,000 kg and 165,000 kg (Table 1) respectively. To meet the current off-take, Village 2 requires a forest area of at least 317 hectares and Village 3 requires a forest area of at least 456 hectares.

Village interviews

Most villages had access to forest areas which provided timber products, notably firewood, timber and poles, in addition to NTFPs. Informants mentioned NTFPs including the provision of shade, medicinal products and fruit as the additional ecosystem services that people gained from trees (Appendix S7). Harvesting of timber often involves felling of large trees whereas harvesting of firewood and poles only requires that part of the tree is cut, allowing future regrowth of trees (Appendix S7).

Opinions on the future of trees and village forest areas differed between villages. Informants in villages 1, 2 and 4 desired for trees within the villages to be present for their children and explained that they were planting new trees and replacing trees that are felled (Appendix S7). Village 3 informants were less optimistic about the presence of trees and the village forest in the future, and were concerned that there may be little or no trees left within a few years (Appendix S7). The importance of local markets in providing timber products was emphasised (Village 1 and 2) and attributed to the lack of trees present.

Discussion

The impact of people on aboveground biomass

Research has mainly focused on the growth rates of trees within forest areas, resulting in AGB growth in the land use categories of settlement, cropland and grassland being less well studied. Historically, this is because the majority of timber products were sourced from well-stocked forest areas; however, these have become depleted as a result of deforestation (Kuyah *et al.* 2014). Our results highlight the potential for other

land uses (e.g. settlements) to provide a source for woody biomass and therefore more consideration should be given to trees located outside forest areas.

Within the study area, trees located within forest displayed the largest AGB growth, principally because, whilst smaller than trees situated in other land use categories, they were more numerous. Concomitantly, forested land uses provide a higher carbon store than other land uses (Willcock *et al.* 2014, 2012). Despite this, findings from this study show that a sizable proportion of AGB growth exists in areas outside of forests; supporting other studies, both in Malawi (Zulu 2010) and across the globe (de Foresta *et al.* 2013), which found biomass harvesting activities were undertaken across a range of land uses (Appendix S1).

The modelled AGB growth per hectare for forested land uses was the largest for villages containing many fast growing, large, non-native species such as Pine (*Pinus* spp) and Blue gum (*Eucalytus globulus*) trees which had been specifically planted to provide timber. Growth rates of plantation forests are higher (7000-13,000 kg ha⁻¹ yr⁻¹) than that of natural miombo woodland (530-2740 kg ha⁻¹ yr⁻¹) (Eggleston *et al.* 2006).

Supplementing existing forest with small scale plantations of fast growing, non-native trees to provide timber products is an increasingly common practice within rural villages in Malawi as a result of government policies encouraging investment in plantations in order to meet woodfuel demand (Deweese 1995; Kuyah *et al.* 2014).

However, there are potential ecological implications associated with clearing natural forest and replacing it with plantations including a reduction in: species diversity, soil quality, the supply of NTFPs, microclimate impacts, and increased water consumption for certain species (Burley 2012). Further research into species used for tree stock

replenishment would be valuable to ensure that the species planted are suitable to meet short and long term village needs.

The impact of climate on aboveground biomass

Total AGB modelled using LPJ-GUESS for the Machinga ($67,344 \pm 7,164 \text{ kg ha}^{-1}$) and Zomba Districts ($74,643.64 \pm 6,161 \text{ kg ha}^{-1}$) was larger than that previously documented in miombo woodland ($22,310 - 42,470 \text{ kg ha}^{-1}$) (Shirima *et al.* 2011; Ryan *et al.* 2011; Kuyah *et al.* 2014). This is likely to be attributable to LPJ-GUESS modelling vegetation in the absence of humans. For example, Brown (1997) estimated that the potential average total AGB of African lowland dry forest in the absence of human influence is $92,000 \text{ kg ha}^{-1}$ but due to human influence, the total AGB is closer to $60,000 \text{ kg ha}^{-1}$. Whilst lowland dry forests can be quite different to miombo woodlands, these findings demonstrate the substantial impact human disturbance can have on AGB and thus have implications for the successful utilisation of LPJ-GUESS within miombo woodland, which is characterised by human disturbances such as deforestation, grazing, land conversion, and the cultivation of indigenous and non-indigenous species.

Since LPJ-GUESS simulates vegetation dynamics in response to the climate, the variation in AGB growth is associated with local and regional climatic conditions that occurred between 1995 and 2005. Productivity of miombo woodland is primarily a function of soil moisture and rainfall availability (Ngongondo *et al.* 2011); therefore, a reduction in these environmental variables would impact upon the amount of off-take villagers can harvest sustainably. Malawi experiences inter-annual variability in rainfall, and years that displayed the largest modelled annual decreases in tree biomass within the Zomba

and Machinga Districts (1997, 2000-2002, 2005) coincided with drought conditions in Malawi (Government of Malawi 2010). In addition, natural disturbance such as fire is a frequent characteristic of vegetation dynamics within miombo woodland (Ryan & Williams 2011). LPJ-GUESS incorporates fire disturbance (Smith *et al.* 2001) and this may have also contributed to a decrease in AGB in years that experienced large reductions. Years that showed a reduction in AGB suggest high natural tree mortality, meaning that all off-take within the villages further decreases AGB and is unsustainable. This has large implications for determining the sustainable harvest rate and highlights the importance of incorporating climatic considerations when modelling future sustainability.

Comparing MYRLIN and LPJ-GUESS

There is no single best model or modelling framework to model tree growth; every model has advantages and disadvantages and in many cases more than one model is appropriate for application. The strengths of yield models (e.g. MYRLIN) are often the weaknesses of process models (e.g. LPJ-GUESS) (Porté & Bartelink 2002). MYRLIN and LPJ-GUESS both require different data inputs and subsequently simulate results that cannot be quantitatively compared, for example, at village level.

MYRLIN has the advantage of being an open access model which has the ability to incorporate field survey data and can be adapted to reflect local knowledge of tree species (Vanclay 2003). This study has demonstrated MYRLIN's ability to establish the current baseline of tree cover and growth in different land uses within data deficient areas. Despite this flexibility, a more comprehensive understanding and application of

forest dynamics is required (Appendix S8). Forest yield models assume that climatic conditions remain constant and therefore the tree population in a given area is relatively stable and will return to equilibrium if harvested sustainably (Sileshi 2014). Climate change encompasses variation in conditions that govern tree growth, whereas yield models disregard some important underlying factors of tree productivity (Monserud 2003). Consequently, the usefulness of results derived from MYRLIN may be limited because changing climatic conditions may well mean that future tree growth rates deviate from those observed in the past.

The sustainable harvest rate will vary according to climatic conditions, as highlighted by our LPJ-GUESS results for Malawi. The most useful models are those that are sensitive to the effects of climate change on tree development over long periods (Monserud 2003). LPJ-GUESS can be utilised where site specific information is not available and adapted to incorporate human influence (Pfeiffer *et al.* 2013). LPJ-GUESS has also been used to indicate the influence of future climate change on vegetation dynamics at district and regional level (Hickler *et al.* 2012), however it is difficult to validate results of LPJ-GUESS in data deficient regions that are characterised by human disturbance (Appendix S8).

The limitations of both models indicate uncertainty around the AGB growth rates given here (Appendix S8). Future growth rates will depend on the rate of climate change and its impact on the conditions for tree growth (Appendix S1). A decline in biomass growth would likely negatively impact human wellbeing in the region, although this could be mitigated by introducing new tree species that are better suited to future climatic conditions than the present mix of tree species.

350

351 **Conclusion**

352

353 This study highlights the importance of the inclusion of trees located outside of forest
354 areas in growth studies such as this. The AGB growth rates modelled in this study,
355 provide a useful benchmark against which future changes might be compared and can
356 be used to support sustainable forest management practices alongside the tree planting
357 initiatives that have already been established by local people. Due to anticipated future
358 climate variability and anthropogenic disturbance in Malawi, sustainable future off-take
359 rates should incorporate both these impacts on vegetation dynamics, as well as
360 understanding who benefits from the derived ecosystem services. Such integrated
361 models will provide a more dynamic assessment of the sustainability within data
362 deficient areas, such as the miombo woodlands in Malawi.

363

364 **Acknowledgements**

365 We acknowledge A. Nicholass, D. Alder, J. Sanudi, C. Mazombwe, E. Mbingwani, M.
366 Likoswe, H. Chapama, C. Brough, D. Kafumbata, M. Joshua and the researchers from
367 Leadership for Environment and Development for Southern and Eastern Africa for their
368 assistance with this investigation. Additionally, we thank all of the villagers and the
369 Village Natural Resource Management Committee members for their knowledge,
370 hospitality and assistance. We also thank Thomas Hickler for assistance in using LPJ-
371 GUESS. We also thank three anonymous reviewers, whose comments greatly improved
372 the manuscript.

373

374 **Financial Support**

This research is an output of the project 'Attaining sustainable services from ecosystems through trade-off scenarios (ASSETS)' (NE-J002267-1), funded with support from the Ecosystem Services for Poverty Alleviation Programme (ESPA). The ESPA programme is funded by the Department for International Development (DFID), the Economic and Social Research Council (ESRC) and the Natural Environment Research Council (NERC). Additional funding was provided by the Engineering and Physical Sciences Research Council (EPSRC) Vacation Bursary (EP/L505067/1). Neither funder had any involvement in study design or writing of the report.

Conflict of Interest

None

Ethical Standards

The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008. Our study conforms to national, local and institutional laws and requirements, both in the United Kingdom and Malawi. Where human subjects were used, we obtained express permission and respected their privacy.

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554 **Figure Legends**

555 **Figure 1.** Map of Malawi detailing the main water bodies (shaded) and cities (labelled points).
556 The location of the transect line on which the study sites are located is indicated.

557
558 **Figure 2.** Diagrammatic representation of the establishment of inventory plots.
559

560 **Figure 3.** Above-ground biomass growth within land use categories in the study area, derived
561 from MYRLIN predictions. Error bars display 95% confidence limits.
562

563 **Figure 4.** Above-ground biomass growth for land categories within the villages, derived from
564 MYRLIN predictions. Error bars display 95% confidence limits.

Table 1. Summary of Above-ground biomass (AGB) growth values for land use categories in the villages, derived using MYRLIN. Estimates and 95% confidence limits displayed are based upon AGB in live trees more than 0.5cm diameter at breast height. Key: * Denotes a sample size of 1, therefore 95% confidence intervals cannot be calculated; † Indicates that current off-take has surpassed the AGB growth; § A sustainable harvest rate of 80% of the total AGB growth was assumed (Appendix S5); ‡ Settlement area was derived from ArcMap calculations (Appendix S7).

Village	District	Land Use Category										Village Total					
		Forest			Settlement			Cropland			Grassland						
		AGB growth (kg ha ⁻¹ yr ⁻¹) (95% CI range)		Area (ha)	Total AGB growth (kg yr ⁻¹)	AGB growth (kg ha ⁻¹ yr ⁻¹) (95% CI range)		Area (ha)	Total AGB growth (kg yr ⁻¹)	AGB growth (kg ha ⁻¹ yr ⁻¹) (95% CI range)		Area (ha)	Total AGB growth (kg yr ⁻¹)	Total Village AGB growth (kg yr ⁻¹)	Annual sustainable harvest rate (kg yr ⁻¹) ^{\$}	Total Village off-take (kg yr ⁻¹)	
1	Machinga	314 ± 6	6840	2,147,760	1060 ± 100	3.6	3,816	34.1*	473	16,129	55 ± 0	72	3960	2,171,655	1,737,332	500,337	
2	Zomba	1534 ± 164	209	320,606	1224 ± 208	3.0	3732	341 ± 146	142	48,422	667 ± 134	0	0	372,760	298,208	485,504 [†]	
3	Zomba	1471 ± 3	349	513,379	2419 ± 189	3.0	7,257	681 ± 111	165	112,365	304 ± 254	0	0	633,001	506,401	670,920 [†]	
4	Zomba	4913 ± 92	359	1,763,767	1276 ± 38	2.1	2,679	1.9*	23	44	1074 ± 177	0	0	1,766,490	1,413,192	529,433	

Table 2. The annual modelled above-ground biomass (AGB) of trees and changes in above-ground biomass for grid cells containing the Zomba and Machinga Districts (1995 - 2005), derived using LPJ-GUESS. Key: *AGB estimate based on roots contributing 25% (95% CI, 0.10) of above-ground live tree carbon, from an African literature estimate (Lewis et al. 2009).

Year	Machinga District		Zomba District	
	Cell 1 (Village 1)		Cell 2 (Villages 2,3,4)	
	Total AGB (kg ha ⁻¹)*	AGB growth (percentage change in annual biomass from previous year) (% yr ⁻¹)	Total AGB (kg ha ⁻¹)*	AGB growth (change in annual biomass from previous year) (% yr ⁻¹)
1995	54,210	7.0	39,195	9.1
1996	58,620	8.1	44,235	12.9
1997	54,780	-6.6	46,770	5.7
1998	60,450	10.4	51,360	9.8
1999	65,910	9.0	56,160	9.3
2000	55,650	-15.6	47,700	-15.1
2001	61,185	9.9	52,245	9.5
2002	63,630	4.0	56,475	8.1
2003	44,415	-30.2	62,310	10.3
2004	46,140	3.9	60,480	-2.9
2005	50,820	10.1	38,655	-36.1
Mean ± 95% C.I	67,344 ± 7,164	0.9 ± 7.8	74,644 ± 6,161	1.9 ± 8.8

Figure 1. Map of Malawi detailing the main water bodies (shaded) and cities (labelled points). The location of the transect line on which the study sites are located is indicated.

Figure 1

131x111mm (300 x 300 DPI)

Figure 2. Diagrammatic representation of the establishment of inventory plots.
Figure 2
178x92mm (300 x 300 DPI)

Figure 3. Above-ground biomass growth within land use categories in the study area, derived from MYRLIN predictions. Error bars display 95% confidence limits.

Figure 3
130x78mm (300 x 300 DPI)

Figure 4. Above-ground biomass growth for land categories within the villages, derived from MYRLIN predictions. Error bars display 95% confidence limits.

Figure 4
181x136mm (300 x 300 DPI)

Appendix S1 – Expanded Manuscript

Introduction

Forests and woodlands are among the most important providers of ecosystem services (the benefits provided by nature) worldwide (Millennium Ecosystem Assessment 2005; UK National Ecosystem Assessment 2011). Forest resources have long served as safety nets and supported coping strategies in periods of economic and environmental shocks and are an important part of livelihood strategies in many countries (Cavendish 2000; Fisher 2004; Shackleton & Shackleton 2004). However, environmental degradation, population increase and climate extremes have placed the resources supporting human wellbeing under pressure. Forest resource managers worldwide are now faced with the crucial challenge of providing forest products for the global population despite a reduction in the natural resource base (Peng 2000). Depletion of natural resources has led to an interest in sustainable forest management in an effort to meet the increasing demands of a growing human population whilst also maintaining socio-ecological function (see MacDicken *et al.* 2015) for a full discussion). To manage a forest sustainably requires the balancing of forest productivity, predicted through the use of forest growth models, with off-take rates, known as sustained yield management (Monserud 2003; Nasi & Frost 2009).

Methodology

Study area

The Southern Region ranks highest in the country in terms of population density, poverty incidence, and scarcity of forest resources (Government of Malawi 2010). The mean annual temperature is 22°C and annual rainfall, confined to the period from November to April, ranges from 600 mm to 1225 mm (Ngongondo *et al.* 2011). The elevation of the study area ranges from 625 m above sea level in the low lying areas around Lake Chilwa to 1450 m in the Zomba-Malosa Forest Reserve.

Miombo woodlands supply around 93% of Malawi's energy needs, provide timber and poles for construction and non-timber forest products (NTFPs) for food and income (Nkwanda *et al.* 2008). Rapid deforestation of around 1% per year (Government of Malawi 2010) limits the current and future ability of forests and woodlands to continue to meet the timber and NTFP needs of local people (Nkwanda *et al.* 2008). The problems associated with depletion of miombo woodland resources are further exacerbated by the low productivity of miombo woodlands, resulting in existing levels of wood demand and harvest off-take rates (~15 million m³ per year) far surpassing sustainable yield (~7-8 million m³ per year) (Government of Malawi 2001; Smith *et al.* 2015). However, information on the inventory and productivity

of miombo woodlands in Malawi remains scattered and discontinuous and there is a lack of tree growth data which is required for assessing the sustainability of current tree management (Abbot *et al.* 1997). Even less is known about tree resources outside forests, although it has long been established that NTFPs are frequently collected from non-forest areas.

Establishment of sample plots

In June and July 2013, three 20 x 20 m sample plots were established within each dominant land use (forest [predominantly miombo woodland], settlement, cropland and grassland) of the four study villages, resulting in 48 plots in total. A stratified random sampling technique was used to locate tree inventory plots within each village based on the following protocol: 1) Each village was divided into three equal sections using a village map (Fig. 2); 2) In each section of the village one plot within each land use category was randomly sampled. Where only one area of each land use was present within a section, this was selected. Where multiple areas of the same land use were present, they were assigned a number and selected using a random number generator (Fig. 2, Section 1); 3) A Google Earth image, with village boundaries added via participatory mapping, was used to estimate the length and width of the forest area (Google Inc. 2013). The position of a sample plot was determined by locating the south west corner of the forest area and generating a random number of paces to walk as a percentage of the forest area length. This was then repeated with a second random number along the width of the forest area in order to establish the south western corner of the 20 x 20 m plot (e.g. Fig. 2, Plot F1). Settlement boundaries were less defined, therefore the centre of the settlement was identified by a Village Natural Resource Management Committee (VNRMC) member. The random number generator was used to determine the number of steps to walk north and east to reach the south western corner of the 20x20 m plot. Areas classified as cropland and grassland varied in size considerably and in three (out of 24) instances a 20 x 20 m plot was not obtainable; however, all models were corrected for plot size. Grassland and cropland plots were identified by the VNRMC member who assisted with identifying perimeters from which the area was calculated.

Inventory methods

Vernacular names were translated into scientific names using a three staged methodology: 1) Initially forestry experts from the Forestry Institute of Malawi (FRIM) translated from vernacular to scientific names; 2) Any vernacular names remaining unidentified from step 1 were then researched using literature available in the archives of Kew Royal Botanical Gardens; 3) Finally, an online literature search was undertaken by entering any vernacular names remaining unidentified from step 2 (e.g. Mpindimbi) into ISI Web of Knowledge, Google Scholar, ScienceDirect and Google between 5th September 2013 - 13th February 2014.

Discussion

The impact of people on aboveground biomass

Dewees (1995) suggested that there has been a tendency to assume that trees located outside of forest areas within Malawi are usually left unmanaged. However, as pressure for woodfuel increases, it is predicted that there will be a subsequent increase in the management of trees and the amount of trees planted outside of forest areas to provide NTFPs and timber (de Foresta *et al.* 2013). This seems to be happening in the study area as interviews highlighted that tree planting to replenish and restock the settlement and village forest areas was occurring to meet increasing demand for wood products. Research focussing on understanding the long term household responses to woodfuel scarcity would be beneficial (Zulu 2010; Smith *et al.* 2015), as would an exploration of how demand for timber, poles and woodfuel (often expressed by different people) may interact to lead to increased tree planting.

A new modelling paradigm

The choice of modelling tool is imperative given that climate simulations for Malawi show that temperatures and wet season rainfall are likely to increase, but climate will become more variable (Government of Malawi 2010; Doherty *et al.* 2009). This may coincide with a rising human population and associated demand on natural resources, agricultural conversion and further deforestation (Government of Malawi 2010). Such changes are likely to impact on AGB growth rates and augment forest resource deficits at village and regional level.

Despite limitations highlighted in this study, forest yield and process models are useful initial tools for establishing a baseline growth rate in data deficient landscapes, from which to assess future sustainability. However, there is an increasing demand for forest models to develop beyond simulating tree growth rates to include evaluation of trade-offs between ecosystem services, climate and human impact (Mäkelä *et al.* 2012; Willcock *et al.* 2016a). Sustainable forest management should incorporate the maintenance of ecological functions and contributions to economic and social wellbeing. Assessment of these ecosystem service benefits are beyond the scope of this study, and to date, no comprehensive models exist that can be used to predict all the indicators of sustainable forest management simultaneously (Mäkelä *et al.* 2012). However, there is a rapidly growing literature base and ecosystem modelling tools that incorporate and evaluate interactions between humans and ecosystems across a range of scales (Vigerstol & Aukema 2011). Such multi-ecosystem service models represent the beginning of a new modelling paradigm and may be beneficial for informing the sustainable management of forests in the future (Villa *et al.* 2014). These models still need to be rigorously validated and verified against observed data before application in data deficient areas but should be considered for future assessments.

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Appendix S2 – Tree species list for Zomba and Machinga districts, southern Malawi, and associated growth rates.

Methodology

A three stage approach was used to determine the growth rates and scientific names of plants from vernacular names (Table S1):

- (1) Initially local forestry experts (e.g. from the Forestry Institute of Malawi; FRIM) translated from vernacular (primarily Chichewa, Yao and English) to scientific names;
- (2) Any vernacular names remaining unidentified by step 1 were then researched using literature available in the archives of Kew Royal Botanical Gardens;
- (3) An online literature search was undertaken by entering any vernacular names remaining unidentified by step 2 (e.g. Mpindimbi) into ISI Web of Knowledge Google Scholar ScienceDirect and Google between 5th September 2013 - 13th February 2014.

Table S1. List and translation of species encountered during plot samples within the four villages; brackets denotes multiple spellings.

Vernacular name	Latin name	Growth rate	References
Accacia	<i>Acacia albida</i>	Fast	Binns 1972; Williamson 1975.
Apple	<i>Malus pumila</i>	Fast	Binns 1972; Williamson 1975; E Mbingwani 2013 pers.comm. 5 Sept.
Avocado pear	<i>Persea americana</i>	Slow	Binns 1972; Williamson 1975.
Blue Gum	<i>Eucalyptus camaldulensis</i>	Fast	Williamson 1975; E Mbingwani 2013 pers.comm. 5 Sept.
Cassia	<i>Cassia sp.</i>	Fast	Binns 1972.
Chidima	<i>Psorospermum febrifugum</i>	Slow	Morris 1996; Burrows & Willis 2005.
Chinama	<i>Combretum collinum</i>	Fast	Binns 1972; E Mbingwani 2013 pers.comm. 5 Sept.
Chipisyawago	<i>Dichrostachys cinerea</i>	Slow	Binns 1972; Williamson 1975; Morris 1996; Keay 1989.
Chiputsa	<i>Fagaropsis sp.</i>	Fast	E Mbingwani 2013 pers.comm. 5 Sept.
Chitimbe	<i>Piliostigma thonningii</i>	Medium	Kaey 1964; Morris 1996; Burrows & Willis 2005;
Chitimbi	<i>Piliostigma thonningii</i>	Medium	Binns 1972; Morris 2008
Guava	<i>Psidium guajava</i>	Slow	Binns 1972; Williamson 1975; E Mbingwani 2013 pers.comm. 5 Sept.

India (Indoya / Indya)	<i>Melia azedarach</i>	Fast	Binns 1972; Pedersen et al. 2005; Nordin & Nordin 2005; Mauambeta et al. 2010.
Jatrova	<i>Jatropha curcas</i>	Fast	BERL 2012; E Mbingwani 2013 pers.comm. 5 Sept.
Kakalesi	Unknown	Fast	
Keshya (Keshu/ Keysha)	<i>Senna siamea</i> Synonym: <i>Cassia siamea</i> . / <i>Senna spectabilis</i> Synonym: <i>Cassia spectabilis</i> .	Fast	PLUS 1998; MDA 2009; Brummitt et al. 2007; M Likoswe 2013 pers. Comm. 11 July.
Lemon	<i>Citrus limonia</i>	Medium	Binns 1972; Williamson 1975
Limbo	<i>Diplorhynchus condylocarpon</i>	Slow	Binns 1972
Lonjemange	Unknown	Slow	
Lungano	<i>Erythroxylum emarginatum</i>	Medium	Keay 1989; E Mbingwani 2013 pers.comm. 5 Sept.
Luzi	<i>Brachystegia utilis</i>	Medium	Murray 1922; Gowela et al. 2005; E Mbingwani 2013 pers.comm. 5 Sept.;
Malaena	<i>Gmelina arborea</i>	Fast	E Mbingwani 2013 pers.comm. 5 Sept.
Malayina	<i>Gmelina arborea</i>	Fast	E Mbingwani 2013 pers.comm. 5 Sept.; MDA 2009
Maluwa	Unknown	Slow	
Mango	<i>Mangifera indica</i>	Slow	Binns 1972; Williamson 1975
Masau	<i>Ziziphus mauritiana</i>	Fast	Nyanga et al. 2013
Masuku	<i>Uapaca kirkiana</i>	Slow	Williamson 1975; PLUS 1998.
Masula	Unknown	Unknown	
Matamone	<i>Diplorhynchus condylocarpon</i>	Slow	E Mbingwani 2013 pers.comm. 5 Sept.
Matow(o)	<i>Azanza garckeana</i> Synonym: <i>Thespesia garckeana</i> F.	Medium	PLUS 1998; M Likoswe 2013 pers. Comm. 11 July.

Hoffm.

Maula	<i>Parinari curatellifolia</i>	Slow	Binns 1972; Williamson 1975; PLUS 1998; Morris 1996; E Mbingwani 2013 pers.comm. 5 Sept.
Mauwla	Unknown	Unknown	
Mawola	Unknown	Unknown	
Mbawa	<i>Khaya anthotheca</i>	Medium	Murray 1922; MDA 2009; M Likoswe 2013 pers. Comm. 11 July.
Mbele	Unknown	Medium	
Mbewe	<i>Ozoroa reticulata</i>	Medium	Binns 1972; Williamson 1975; Keay 1989; Kanthungo 2007
Mbindi	<i>Vitex doniana</i>	Fast	E Mbingwani 2013 pers.comm. 5 Sept.
Mbulukututu	<i>Vangueria infausta</i>	Medium	PLUS 1998; E Mbingwani 2013 pers.comm. 5 Sept.
Mchenga	<i>Julbernardia globiflora</i>	Medium	Binns 1972; PLUS 1998; Dondeyne 2004.
Miombo	<i>Brachystegia sp.</i>	Fast	Williamson 1975; E Mbingwani 2013 pers.comm. 5 Sept.
Mkalati	<i>Burkea africana</i>	Medium	Williamson 1975; UNFAO 2005.
Mkokona-Scimba	<i>Stereospermum kunthianum</i>	Fast	Murray 1922; Dondeyne 2004.
Mkarti	Unknown	Slow	E Mbingwani 2013 pers.comm. 5 Sept.
Mkrati	<i>Ozoroa insignis</i>	Slow	Chettleborough et al. 2000.
Mlima	<i>Vangueria infausta</i>	Slow	E Mbingwani 2013 pers.comm. 5 Sept.
Mlonga	<i>Acacia polyacantha Willd.</i>	Fast	Binns 1972; Williamson 1975; Keay 1989.
Mlundo	<i>Dalbergiella nyasae</i>	Fast	Williamson 1975; Kanthungo 2007
Mlungwe	<i>Dalbergia nitidula</i>	Slow	Binns 1972; Williamson 1975.
Mmbewe	<i>Markhamia obtusifolia</i>	Medium	E Mbingwani 2013 pers.comm. 5 Sept.
Mombo	<i>Brachystegia boehmii</i>	Fast	Williamson 1975; PLUS 1998; Kanthungo 2007.
Mpapa	<i>Brachystegia spiciformis</i>	Fast	Binns 1972; UNFAO 2005; Kanthungo 2007.

Mpindimbi	<i>Vitex doniana</i>	Unknown	Williamson 1975; Binns 1972; E Mbingwani 2013 pers.comm. 5 Sept.; Dondeyne 2004
Mpoloni	<i>Steganotaenia araliacea</i>	Fast	Keay 1989; PLUS 1998; UNFAO 2005.
Mposa (Mpoza)	<i>Annona senegalensis</i>	Fast	Williamson 1975; Binns 1972; Kanthungo 2007
Msangwa	<i>Kigelia africana</i>	Slow	Neuwinger 1994
Msangwi	Unknown	Slow	
Msasi	<i>Ricinus communis</i>	Fast	E Mbingwani 2013 pers.comm. 5 Sept.
Msolo	<i>Pseudolachnostylis maprouneifolia</i>	Medium	UNFAO 2005
Msora	<i>Rawsonia usambarens</i> Synonym: <i>Rawsonia lucida</i> Harv. & Sond.	Fast	E Mbingwani 2013 pers.comm. 5 Sept.
Msuku/masuku	<i>Uapaca kirkiana</i>	Slow	Murray 1922; Williamson 1975
Mtanga(m)tanga	<i>Albizia lebbek</i>	Fast	Murray 1922; Binns 1972; Mauambeta et al. 2010.
Mtewelere	<i>Cassia petersiana</i>	Unknown	Binns 1972
Mtomoni	<i>Diplorhynchus condylocarpon</i>	Medium	Williamson 1975; Dondeyne 2004
Mtongongou	Unknown	Unknown	
Mtundu	<i>Ficus capensis</i>	Fast	Williamson 1975
Mtwana	<i>Brachystegia busse</i>	Fast	Burrows & Willis 2005
Muliri	Unknown	Unknown	
Mulmbua	Unknown	Unknown	
Mulombwa	<i>Pterocapus angolensis</i>	Unknown	E Mbingwani 2013 pers.comm. 5 Sept.; Murray 1922
Mvula	<i>Isobertinia angolensis</i>	Fast	Binns 1972; E Mbingwani 2013 pers.comm. 5 Sept.
Mvunguti	<i>Kigelia africana</i>	Slow	Williamson 1975
Mwanga	<i>Pericopsis angolensis</i>	Slow	Williamson 1975
Mwlonge	Unknown	Unknown	
Mwolo	Unknown	Unknown	

Naphini	<i>Terminalia sericea</i>	Fast	Murray 1922; Binns 1972; M Likoswe 2013 pers. Comm. 11 July.;
Nchenga	<i>Brachystegia sp.</i>	Fast	Murray 1922
Ndhundu	Unknown	Fast	
Nesela	<i>Antidesma venosum</i>	Unknown	E Mbingwani 2013 pers.comm. 5 Sept
Npini	<i>Terminalia sericea</i>	Unknown	Burrows & Willis 2005; E Mbingwani 2013 pers.comm. 5 Sept;
Nsachera	Unknown	Slow	
Nsangwa	Unknown	Unknown	
Nsolo	<i>Choristylis rhamnoides</i>	Fast	Binns 1972; E Mbingwani 2013 pers.comm. 5 Sept.
Nsondoka	<i>Ziziphus mauritiana</i> Synonym: <i>Ziziphus abyssinica</i> (Hochst)	Fast	Keay 1989; E Mbingwani 2013 pers.comm. 5 Sept.
Nsopa	<i>Bridelia micrantha</i>	Fast	Keay 1989; Binns 2004; E Mbingwani 2013 pers.comm. 5 Sept.
Ntandanyerere	<i>Byrsocarpus orientalis</i> Synonym: <i>Rourea orientalis</i> Baill	Fast	Binns 1972; Williamson 1975; PLUS 1998.
Ntate	Unknown	Slow	
Ntatu	<i>Allophylus africanus</i>	Slow	Keay 1989
Ntawa	<i>Flacourtia indica</i>	Slow	Binns 1972
Ntewelege	<i>Cassia singueana</i>	Slow	Binns 1972; Williamson 1975.
Ntewerere	Unknown	Slow	
Nthanga	Unknown	Unknown	
Nthema	Unknown	Medium	E Mbingwani 2013 pers.comm. 5 Sept.
Ntondu	Unknown	Unknown	
Ntonongoli	<i>Vitex mombassae</i>	Fast	Binns 1972; PLUS 1998.
Ntothwa	Unknown	Fast	
Ntoto	<i>Isobertia tomentosa</i>	Fast	E Mbingwani 2013 pers.comm. 5 Sept.

Nyenye	<i>Newtonia hildebrandtii</i>	Slow	Morris 1996.
Nyowe	<i>Syzgium cordatum</i>	Fast	Binns 1972; Williamson 1975; E Mbingwani 2013 pers.comm. 5 Sept.
Nziru	Unknown	Fast	
Orange	<i>Citrus sinensis</i>	Medium	Binns 1972; Williamson 1975.
Papaya	<i>Carica papaya</i>	Fast	Keay 1989; Binns 1972; E Mbingwani 2013 pers.comm. 5 Sept.
Peach	<i>Prunus persica</i>	Fast	Binns 1972; Williamson 1975; E Mbingwani 2013 pers.comm. 5 Sept.
Phikiwamaungu	Unknown	Unknown	
Pine	<i>Pinus sp.</i>	Fast	Williamson 1975.
Sambafumu	<i>Azelia quanzensis</i>	Medium	Burrows & Willis 2005; MDA 2009; E Mbingwani 2013 pers.comm. 5 Sept.
Sechela	Unknown	Fast	
Sendelener	Unknown	Unknown	
Sendelera/sendelere/sendereya	<i>Toona ciliata</i>	Medium	Williamson 1975; Keay 1989; E Mbingwani 2013 pers.comm. 5 Sept.
Sukachuma	Unknown	Slow	
Taida	<i>Pine sp.</i>	Fast	
Tandanyerere	<i>Phyllanthus guineensis</i> Synonym: <i>Phyllanthus ovalifolius</i> Forssk.	Slow	Binns 1972; UPM 1975; E Mbingwani 2013 pers.comm. 5 Sept.
Tangarine	<i>Citrus reticulata</i> Blanco	Fast	
Thombozi	<i>Diplorhynchus condylocarpon</i>	Slow	Binns 1972; UNFAO 2005; Morris 2009.
Uwaowa	<i>Monotes africanus</i>	Slow	Morris 1996.
Wuwa wuwa	Unknown	Slow	

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Appendix S3 - MYRLIN: Data input and species grouping.

Model Description

Methods of Yield Regulation with Limited Information (MYRLIN; Figure S3.1) is a toolkit comprising of three tools designed to calculate timber yield for forests using limited information (Alder *et al.* 2002). MYRLIN is based upon a simple diameter-class projection (Wright & Alder 2000) which allows the projection of stand tables in order to estimate growth rates. MYRLIN is directed at organisations with a limited research base of information on forest dynamics (van Gardingen 2003).

Figure S3.1 Schematic of the MYRLIN methodology.

Table S3.1 Main functions of the MYRLIN #1 tool and values inputted into the model.
Adapted from Nicol *et al.* (2002).

Function and Features	Comment	Values used
<u>PlotData</u>	<u>PlotData</u>	N/A
Data can be stratified by suitable column in the plot data (dbh/species/tree id.) as required.	Stratum (land use category), Plot number, tree number, species vernacular name and tree diameter data were inserted into PlotData sheet.	
<u>SpList</u>	<u>SpList</u>	N/A
Species vernacular name and scientific name can be entered but are not used by MYRLIN. A species group column is needed to reflect difference in ecology.	Species vernacular and scientific name were entered into the sheet in addition to species groups:	
Species list can be sorted by Genus/Species or grouped by growth rate.	<ul style="list-style-type: none"> • Fast • Medium • Slow • Unknown 	
<u>Areas</u>	<u>Areas</u>	0.04ha
Macro <i>StratumRecordCount</i> can be used to calculate the number of records in each sample plot.	Area (ha) of plots is required.	
<u>StandTables</u>	<u>StandTables</u>	Diameter classes were changed to include trees over 0.5cm dbh.
The following area units can be used:	Stems per km ² was chosen.	
<ul style="list-style-type: none"> • Stems per km² • Stems per ha • Basal area per ha 		
Flexible diameter limits can be employed within the stand tables.		Diameter class widths of 10cm were chosen.

Methodology

The MYRLIN toolkit comprises three Microsoft Excel workbooks with embedded macros. MYRLIN #1 and MYRLIN #2 were utilised in this study (Figure A3.2)

Figure S3.2 Flowchart of displaying the main data inputs and process of the MYRLIN toolbox.

MYRLIN #1

MYRLIN #1 uses inventory plot data to produce stand tables, required for modelling tree growth rates. Tree diameter at breast height (dbh), species name and grouping value and area of plot are the input data required (Table S3.1).

MYRLIN #2

MYRLIN #2 uses the data from MYRLIN #1 to estimate annual diameter increment (Dinc) for each species group (Table S3.2). This is based upon the mean regression of worldwide tropical forest data (Alder *et al.* 2002).

Table S3.2 Main functions of the MYRLIN #2 tool and values inputted into the model.
Adapted from Nicol *et al.* (2002).

Function and Features	Comment
Species group values can be adjusted on the graph based on knowledge of ecological characteristics.	<p>Species growth rates adjusted to fit ecological characteristics:</p> <ul style="list-style-type: none">• Fast growth = blue line• Medium growth = red line• Slow growth = yellow line <p>Trees with unknown growth rates were left as default as ecological characteristics could not be determined.</p>

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Appendix S4 - Calculation of settlement land cover within the villages.

Table S4. Calculated area of homestead and settlement areas within the villages based upon a

Village	District	Number of houses	Mean area of a homestead (m ²)	Total area of settlement (m ²)
1	Machinga	258	140.5 ± 7.5	36,249
2	Zomba	226	131.2 ± 7.4	29,651
3	Zomba	252	119.4 ± 6.7	30,089
4	Zomba	190	110.6 ± 6.9	21,014

sample of 100 randomly selected households within the village using ArcMap 10.1 software.

Appendix S5 - Wood off-take rates in southern Africa.

Table S5. Summary of literature review providing annual consumption of wood per capita. Key: * denotes the off-take rate chosen to represent the annual per capita consumption of wood within the villages studied.

Wood consumption (kg per capita ⁻¹ year ⁻¹)	Location of Study	Year of Study	Additional Notes	Reference
574	Sikonge District, Tombola Region, Tanzania	2013	Fuelwood and charcoal	Masanja 2013.
570.51*	Southern Malawi	2009	Firewood, residues and charcoal; Rural per-capita consumption	GOM 2009.
676.02	Central Malawi	2009	Firewood, residues and charcoal; Rural per-capita consumption	GOM 2009.
706.43	Northern Malawi	2009	Firewood, residues and charcoal; Rural per-capita consumption	GOM 2009.
657	Pimbwe, Tanzania	2007	Fuelwood only	Homes 2007.
538.8	Rolle, South Africa	2007	Fuelwood only	Madubansi & Shackleton 2007.
473.2	Tanzania	2004	Fuelwood only	Biran et al. 2004.
525.2	Lake Malawi	2004	Fuelwood only	Abbot 1996.
692 ± 53	Limpopo Province, South Africa	2004	Fuelwood only	Dovie et al. 2004.
560.8	Mulanje Forest reserve	2000	Fuelwood only	Orr 2000.
677.2	Dzalanyama, Central Malawi	2000	Fuelwood only	Orr 2000.
288.3	Liwonde, Southern Malawi	2000	Fuelwood only	Orr 2000.
525.2	Lake Malawi	1999	Fuelwood only	Abbot and Homewood 1999.
576	Rumphi District, Northern Malawi	1998	Fuelwood only	Zana 1998.
478.2	Ntheu district, Malawi	1997	Fuelwood only	Brouwer et al. 1997.
468	Ntheu district, Malawi	1997	Fuelwood only	Brouwer et al. 1997.
514.8	Ntheu district, Malawi	1997	Fuelwood only	Brouwer et al. 1997.
687 ± 48.8	South Africa	1993	Fuelwood only	Shackleton 1993.
742	South Africa	1986	Fuelwood only	Eberhard 1986.

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Proof for Review

Appendix S6 - Maximum sustainable yield.

The concept of maximum sustainable yield in forestry has developed from the management of natural resources, such as fisheries, and involves setting sustainable yield limits that can be achieved over time whilst ensuring that productive capacity of the resource is maintained (Hilborn *et al.* 1995; Luckert & Williamson 2005).

Sustainable harvesting requires more than just a reproductive surplus as methods of wood harvesting can result in: reduction in soil productivity and erosion, deterioration of hydrological functions and damage to surrounding trees, e.g. damage to foliage and branches (Hilborn *et al.* 1995; UNFAO 1998). An annual sustainable harvest rate needs to be applied to the total above-ground biomass (AGB) growth modelled at village level in order to account for these factors. Following Outuoma *et al.* (2011) an annual sustainable harvest rate of 80% was applied to the total AGB growth modelled for the individual villages:

$$\text{Annual sustainable harvest rate (kg yr}^{-1}\text{)} = \text{Total Village AGB growth (kg yr}^{-1}\text{)} \times 0.8$$

This equates to an Annual Allowable Cut (AAC) which can be modelled for each village in order to calculate the current sustainability.

To obtain a sustainable harvest rate that is applicable and representative of the above-ground biomass growth in individual villages, data is required on the time trees of varying species take to mature, the regeneration success of trees subsequent to harvesting and the impact of natural disturbances (e.g. wildfires).

Utilisation of an annual allowable cut figure has limitations when used by itself, or if it becomes the overriding objective of forest management (Vanclay 2014). Natural ecological influences impact upon the utility of AAC when implemented as volume control because the long-run average growth may not occur each year (Eneya *et al.* 2004). In years which experience low productivity, use of an AAC will lead to overharvesting (Vanclay 2014). In addition, the setting of AAC values assumes that demand for wood remains constant.

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Proof for Review

Appendix S7- Village interviews.

Table S7. Interview data from villages regarding current tree management and the sustainability outlook for the village.

Village	Where do villagers obtain the following forest products from within the village?			How much of the tree is utilised?			Expected lifetime of the forest and reason.	Amount of time they want forest to last and reason.	Additional comments
	Timber	Woodfuel	Poles	Timber	Firewood	Poles			
1	Timber is mainly purchased from the market due to a lack of large trees. Any large trees present within the forest area are utilised for timber.	Any tree.	Straight trees in the village forest.	The whole tree is harvested.	The tree is pruned to allow harvesting of firewood and is then left to re-grow before harvesting again.	The tree is pruned to allow harvesting of poles and is then left to re-grow before harvesting again.	Forever. Trees are currently being planted to replace trees that are cut down.	Forever so they can keep using the trees.	Trees in the settlement provide: fruit (e.g. Mango, Apple and Avocado trees), medicinal products and shade. These trees are not used for woodfuel. The main land use consists of rice paddy fields. Rice is sold to local markets.
2	N/A. Timber is purchased from the market as there are not many trees large enough to provide timber within the Village.	Trees around settlement.	Small straight trees.	N/A	Branches measuring approximately 1 metre in length are taken from trees. The rest of the tree is left to allow regrowth.	Straight branches of trees are used. The rest of the tree is left to allow regrowth.	Not known.	Forever. By replanting trees it will enable the next generation to have easy access to trees.	Currently different species of trees are being planted within the settlement and forest areas to ensure that timber and non-timber forest products can be sourced by the villagers. The village chief is making sure that large trees within the forest and settlement areas are being left as these provide shade.

									Timber, poles and woodfuel are bought from market when not available within the village.
3	Village forest areas.	Any large tree.	Any straight trees.	The whole tree is harvested.	Only part of the tree is harvested to allow regrowth.	The whole tree is harvested.	If current harvest rates continue, there will be no large trees left within one year.	Four years. This is the time that it will take for trees to grow large enough to use or sell.	Their children will have problems in the future as there will not be enough trees. If this occurs then people will buy wood from the market and from other villages who have kept their trees and forests. Trees that are cut down in the village have to be replanted.
4	Full grown trees in the village forest areas.	Village forest areas.	Any straight trees.	The whole tree is harvested.	The tree is pruned to allow harvesting of firewood and is then left to regrow before harvesting again.	The tree is pruned to allow harvesting of firewood and is then left to regrow before harvesting again.	Forever. Trees are currently being planted to replace trees that are cut down and to create more forest areas.	Forever.	Trees in the settlement provide fruit and shade therefore these are not cut down completely. Trees within the forest are used for medicine and for collecting wild fruit.

Appendix S8 – Model Assumptions and Limitations.

Assumptions and limitations of MYRLIN

Allometric equations and wood density

MYRLIN is based on data from humid tropical forest species. This has resulted in effective implementation in many tropical locations (Nicol *et al.* 2002; van Gardingen 2003), but is not known to have been utilised within miombo woodland (D. Alder personal communication, 3 March, 2014). Converting MYRLIN output (DINC) to AGB growth required a number of assumptions including an average wood density value and a generalised allometric equation. This can lead to inaccuracies when estimating the biomass of individual tree species (Chave *et al.* 2004) due to the influence of local environmental variables (Fonseca *et al.* 2012). Wood density data is rarely available in the tropics (McWilliam *et al.* 1993) and few allometric equations developed specifically for miombo woodland exist (Abbot 1999; Frost 1996; Ryan *et al.* 2010). Despite this, the AGB growth per hectare modelled within this study is comparable with other studies undertaken within miombo woodland (e.g. Guy 1981; Chidumayo 1990; Frost 1996).

Land cover estimation

The validity of village level results was largely influenced by the calculated area of land use categories derived from the Globcover map.

Grassland was present in all villages, despite Globcover failing to identify its existence within Villages 2, 3, and 4. Similarly, in Village 1 the local community, supported by field observations, categorised the majority of the village land use as cropland (rice paddy fields), rather than the forest cover suggested by Globcover. This may be because the land use has changed since the map was produced, or because the resolution was not sufficient to accurately determine the land use categories. In addition, Globcover does not provide data defining the area of settlement within each village.

The last national forest map was produced using Landsat in 1992 (GOM 2010) and as human influence is having a rapid and substantial impact upon the tree cover in Southern Malawi, the provision of current, more resolute images or maps would enable more accurate determination of land use categories. This would improve future estimations of sustainability at village level and allow more informed management decisions from local bylaws to national policies.

Off-take rates

To assess the sustainability of current off-take, this study assumes that all wood is sourced from the village and that the consumption in villages is equal. In reality, wood may be sourced from local markets and per capita consumption rates are likely to vary between and within villages, with larger households consuming less wood per capita than smaller

households (Biran *et al.* 2004). Household surveys within the villages are currently being conducted by ASSETS researchers to enable more accurate off-take data.

Assumptions and limitations of LPJ-GUESS

Cell dynamics

The largest variations in AGB growth between the districts occurred in 2003 and 2005. However, due to the proximity of the districts, it seems improbable that the climate would vary substantially between adjacent cells. LPJ-GUESS models grid cells independently (Smith *et al.* 2001), and therefore processes may not affect neighbouring cells resulting in disparate results between adjacent cells. In reality, adjacent cells are likely to be affected by species dispersal, local climatic conditions, fire and runoff fluctuations.

Human influence

Miombo woodlands have been subject to anthropogenic modification, thus LPJ-GUESS results, modelled under the sole influence of natural processes, are likely to be larger than actual AGB growth rates. This has also been identified as a limitation when applying LPJ-GUESS to other human modified landscapes (Tang *et al.* 2010).

Resolution

The resolution of the LPJ-GUESS grid cells ($0.5^\circ \times 0.5^\circ$) meant that estimates of AGB growth cannot be calculated for the different land use categories modelled using MYRLIN or to individual village estimates within the Zomba District.

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