Progress Report for Phase II
Part I from Paul V. Desanker
(Part II from Peter Frost attached)

Coupling Land Use and Land Cover Changes, and Ecosystem Processes in Miombo Woodlands Grant Number: NAG5-6384

Introduction

This repot covers the second phase o the NASA LCLUC Miombo Project. The project is progressing very well, and has started to produce results from both the US and the Zimbabwe side. A progress report of the Zimbabwe side of this project by Peter Frost (Co-PI) is attached.

One graduate student has completed his PhD studies (Malanding Jaiteh, Nov 1999), and a Masters student (Sarah Walker) is expected to graduate by the end of this project. Methods for processing Landsat TM data in miombo have been developed and tested, and work has begun to do bulk processing of data in-hand. This phase involved a lot of data processing and development of methods. These should come together into answering science questions during the final phase of this project.

Landsat TM Processing in Miombo

Land cover mapping at national levels in Southern Africa has mostly been based on visual interpretation methods of printed images. This is obviously time consuming, expensive and very subjective. We tested various digital classification methods to arrive at a satisfactory scheme that produced adequate accuracy (minimum of 80%).

A Hybrid Classification Scheme was developed after an extensive comparison of supervised and unsupervised techniques. Accuracies achieved are given in Table 1, and Figure 1 shows the flow chart for the scheme adapted for processing TM in miombo, which we are calling the Stepwise Thematic Classification (STC) method.

Table 1. Comparison of overall accuracy (%) and kappa statistics for unsupervised, supervised, and Stepwise Thematic Classification procedures.

Classification Method	Producer's accuracy (%)	User's Accuracy (%)	Kappa Coefficient
Unsupervised classification	46	52	0.34
Supervised Classification	29	64	0.57
Stepwise thematic classification	88	85	0.81

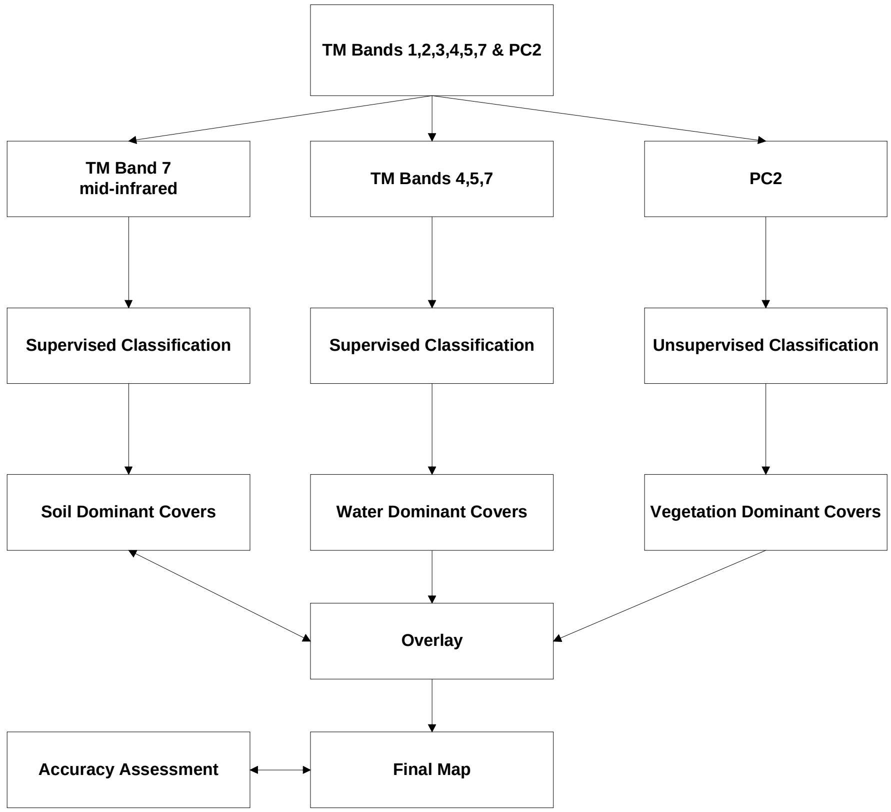

Figure 1. Flowchart of stepwise thematic classification method adapted for the Miombo TM data analysis

The Stepwise Thematic Classification method was used to classify Landsat TM data for three sites (2 to 3 dates at each site), in Kasungu (Malawi), Mutoko and Mzola (Zimbabwe). Landscape statistics were calculated using the FRAGSTATS program (McGrigal and Marks, 1994). This component of the project was the core of Malanding Jaiteh's thesis work, and three manuscripts have been submitted or are being finalized for submission to peer-reviewed journals:

Jaiteh, M.S., and P.V. Desanker (submitted). *Comparisons Of Supervised And Unsupervised Classification Of Landsat Tm Data For Miombo Land Cover Mapping*.

Jaiteh, M.S. and P. V. Desanker (submitted) *Computer-Assisted Classification Of Landsat TM Data For Miombo Land Cover Mapping.*

Jaiteh, M.S., P.V. Desanker, and J. Chen. (to be submitted) *Spatial And Temporal Characteristics Of Landscape Change In The Miombo*

We are now processing a large number of scenes covering up to 10 sites in the miombo for use in a miombo-wide land cover change model. Previews of the scenes being processed (including the latest Landsat 7 ETM+ scenes are available on the miombo web page at http://miombo.gecp.virginia.edu/data/landsat7).

Regional Mapping

As part of the Miombo Network, we have developed a regional land cover map for the miombo countries (Tanzania, Mozambique, Malawi, Zimbabwe) from the best available national land cover maps. Most of the inputs were based on national mapping that utilized 1990's Landsat TM data, interpreted using visual classification techniques. The different legends were harmonized into a standard set suitable for regional application, including future GOFC mapping. Data for Tanzania were available as 64 separate maps that were drafted independent of neighboring maps. These were joined and cleaned extensively to produce continue classes across maps. A forest map for Mozambique was digitized from a hard copy version. Maps for Tanzania, Mozambique, Malawi and Zimbabwe using the harmonized legend are now available. Zambia maps are being digitized, while there is currently little information available as inputs for the Democratic Republic of the Congo and Angola. A strategy for monitoring landscapes is proposed based on recent satellite data to show degree of disturbance and fragmentation, especially over reserve areas and areas undergoing rapid changes due to changing land uses. Landsat 7 data taken during July-September of 1999 were used to demonstrate this monitoring idea, and they already show some dramatic land cover changes in areas that were intact during the early 1990's. The maps are being prepared for access via the Miombo Web Site (http://miombo.gecp.virginia.edu). This work received supplemental funding from the US WWF office. A manuscript has been prepared and submitted, titled:

The Miombo Regional Land Cover Map: First Results and Suggestions for a Land Cover Change Monitoring Activity; by Paul V. Desanker, Malanding S. Jaiteh, Dominick Kwesha, Manuel Ferrao, Pius Yanda, and Quanfa Zhang.

Table 2 shows the structural characteristics used to define the land cover classes in the harminised legend, and Tables 3 and 4 show the harmonized legend and a summary of areas by major cover type, by country.

Table 2. Structural characteristics of vegetated cover classes derived from classification schemes used in the miombo countries.

Height		>15m	15-5 m	5-1 m	<1 m
Canopy	100-70%	Natural Forest	-	-	-
	100-70%	Forest Plantation	Forest Plantation	Forest Plantation	Forest Plantation
	70-20%	-	Woodland	Thicket	Thicket
	20-2%	Wooded Grassland	Wooded Grassland	Bushland	Bushland
	<2%	Grassland	Grassland	Grassland	Cultivation

Table 3. Harmonized legend integrating classifications used in producing national maps and the University of Maryland's (Umd) 1 km land cover product (the codes under each country in columns 2-5 refer to legend entries in the individual country maps).

Land Cover Class	Malawi	Zimbabwe	Mozambique	Tanzania	UMd
1. Natural Forest					
1.1 Moist natural forest	Fe	1	1.1,1.2,1.3,2.1	Fn	2,4,5
1.2 Mangrove			5.0	Fm	
2. Forest Plantation					
2.1 Conifer	Fp	2		Fp	1
2.2 Hardwood					
3. Woodland					
3.1 Closed Woodland	Fbh, Fbf	3	2.2,2.3	Wc	6
3.2 Open Woodland			3.1,3.2	Wo	
4. Bushland/Shrubland					
4.1 Intact Bushland/shrubland		4		Bd,Bo,B(et), Bt,Bt(et)	8,9
4.2 Degraded Bushland			3.3	BSc)	5
5. Wooded Grassland					
5.1 Wooded grassland	Os	5	4.1	Gw,Gb,	7
5.2 Dambos (wooded)				Gws, Gbs,	
6. Grassland					
6.1 Grassland	Og	6	4.2	Go	10
6.1 Dambos	Od			Gos	
7. Bare Area					
7.1 Natural Bare Areas	Nb Nr	9	6	BSL,SC,RO,ICE	12
8. Water Bodies					
8.1 Inland Water	8	9	8	IW	0
8.2 Ocean				Ocean	
9. Swamps and Marshes					
9.1 Fresh	SM			S/M	
9.2 Salt flat				SC	
10. Cultivation					
10.1 Intensive	Ia	7	7	Cm,Ctc,Ctc(st),Cbc,Chc	11
10.2 Extensive	Ef Eg				
11. Builtup Area	Built up	10	Nil	Built up	14

Table 4. The area (km^2) and proportion (%) of land cover classes in miombo countries.

Land cover types	Tanzania		Zimbabwe		Mozambique		Malawi	
	Area (sq.km)	%	Area (sq.km)	%	Area (sq.km)	%	Area (sq.km)	%
Nodata	165	0.02	0	0	1917	0	0	0.00
Natural Forest	25911	2.49	107	0.03	21798	2.76	828	0.69
Forest Plantation	1313	0.13	1562	0.40	0	0.00	1418	1.18
Woodland	305446	29.37	208683	53.36	297675	37.62	25357	21.19
Buashland/ Shrubland	80974	7.79	49777	12.73	154172	19.49	0	0.00
Wooded Grassland	110302	10.60	12184	3.12	148242	18.74	394	0.33
Grassland	36402	3.50	6826	1.75	41492	5.24	7071	5.91
Barren land	1187	0.11	576	0.15	593	0.07	0	0.00
Water	156135	15.01	2977	0.76	5654	0.71	24430	20.41
Swamp/Marsh	9629	0.93	0	0.00	0	0.00	1733	1.45
Cultivation	312068	30.00	107008	27.36	119639	15.12	58215	48.65
Built-up area	566	0.05	1377	0.35	0	0.00	225	0.19
Total	1040098	100	391077	100.00	791184	100	119671	100.00

Application of the Regional Map to Questions of Carbon

The regional map described above was used to estimate broad carbon pools in the miombo countries, and the results are shown in Table 5.

Table 5. Rough estimates of Distribution of Aboveground Carbon in Different Land Cover Types in Countries of the Miombo Calculated using areas from 1990 land cover maps (derived from TM data) and vegetation carbon density values from Houghton et al. (1983)

	Mozambique	**Malawi**	**Tanzania**	**Zimbabwe**	**Zambia**
	Distribution of Above Ground Carbon in Cover Type by Country (%)				
Natural Forest	18	9	22	<1	31
Forest Plantation	-	16	1	3	-
Woodland	41	45	43	69	59
Shrub and Wooded Grassland	35	10	22	19	9
Cultivation	3	19	8	7	-
% Land in Natural forest/forest plantation	3	2	3	<1	7
% Land in woodland	38	27	34	54	76
Above ground Carbon estimate (~Year 1990) x10E9 kg	1,970	1 47	1,900	812	2,560
Land Area (sq km)	784,090	94,080	886,040	386,670	740,720

** The percents do not add up to 100 as other land cover categories are not reported that make up the land area. Not all countries had all categories represented in their maps, hence gaps in reported areas e.g. cultivation for Zambia. These data are approximate, but show the relative importance of various land cover types with respect to carbon content. Vegetation carbon density values are from Houghton et al. (1983). Natural forests and plantations have 16 kg C/m^2, while woodlands have 2.7, shrublands and wooded grasslands 1.8 and cultivated areas 0.5. Zambia land cover estimates are based on Chidumayo (1995).*

Main findings:

- Zambia, Mozambique and Tanzania have the most carbon in biomass in the miombo countries, most of which resides in woodlands (mainly miombo, but also Kalahari woodlands, *Terminalia* woodlands and *Acacia* types). Zimbabwe has medium carbon while Malawi has a low carbon content (Malawi is very small in total area compared to the other countries.
- Except for Zimbabwe, the other countries have between 18-31% of their carbon in natural and forest plantations, which make up less than 7% of their land. Zimbabwe and Zambia have the most of their carbon in woodlands systems.
- Zambia, with the most carbon, does not yet have a national land cover map based on Landsat TM like the others. No data exists for Angola to the best of our knowledge.

These observations highlight the need for improved carbon densities and the need to have reliable baseline land cover maps. The majority of the carbon in woodlands is at risk of being converted to much lower carbon density in cultivated areas, or grassland systems as a result of increasing human pressure. Low carbon densities in woodland and grassland systems mean that forest plantations using exotic species like pines, are the most feasible mechanism for building up carbon stores through afforestation in this region. We are adapting existing forest growth and yield models to generate carbon outputs, and will incorporate them in the overall land use change model to allow a realistic analysis of carbon dynamics.

On-going Below-ground Carbon Work

A Master's student, Sarah Walker, has set up a study of carbon in the soils of miombo. Analysis of soil samples from sites in Malawi is in progress. Samples were taken at sites of a known land use history, going back to 40 years of farming, and various lengths of woodland recovery after abandonment (up to 70 years). This work is expected to reveal how carbon levels differ among land use types, and how soil carbon recovers after abandonment. Analysis of patterns with depth will further explore complex patterns observed elsewhere by King and Campbell (1994) in Zimbabwe.

Modeling: Climate Data Inputs

Climate data are a major constraint to modeling (both ecological and land use change), especially in Southern Africa where weather stations are very sparse. While long-term averages are relatively easily accessed, daily records are not, and most national meteorological centers do not have computer-based databases for further distribution of their data to the public. With core, funding from the EU through START, we organized a workshop in April 1999 and invited data analysts from several Southern African countries. We discussed issues of data access, and jointly designed a web-based template for each country to use to archive and distribute their data. A report of this workshop is available a CD-ROM or via the web at http://miombo.gecp.virginia.edu/climatecd). Daily climate records previously unavailable through normal climate archives (such as the NOAA/ORNL archives) have been processed for Mozambique and Zambia, as well as Malawi and Zimbabwe. Work is in progress to add data from Tanzania. These data will be analyzed to provide summaries of extreme events for input into the vegetation and fire models. Stochastic weather simulators will also be parameterized. Further development of this database will produce a very useful resource for modelers and related global change activities over Southern Africa.

Modeling: MELT Model Implementation in Progress

The ultimate results of this project will be encapsulated in an integrating model of land use change, which we are calling MELT (Miombo Ecosystem Land Transformation Model).

The full model will have a graphics user interface built on top of a Landscape Modeling Shell called (LAMOS by Ian Noble et al. at the IGBP GCTE Office and Australia National University, in Canberra, Australia). LAMOS includes all the common patch scales algorithms for patch-scale vegetation dynamics (gap-phase, vital attribute functional approaches, Markov chain); landscape disturbances such as fire (cellular automata, Markov chains, various percolation algorithms) and for lateral flow of materials across cells. LAMOS is best suited for small landscapes, and so far emphasizes fire, and works in situations where rules apply equally to the whole model space. We are extending LAMOS (in collaboration with the developers of LAMOS) to include large landscapes with strata such as land ownerships, where the rules apply differently depending on a combination of strata attributes.

LAMOS is object oriented, and includes patch dynamics models that were included in their MUSE shell (Ian Davies and Ian Noble). The miombo patch dynamics model MIOMBO, has already been incorporated into MUSE, and is ready to work with LAMOS. Major additions to the existing LAMOS shell will be external modules that will compute land use change factors (LUCFs) as a function attributes from the miombo region (population, ownership, soil potential, climate, etc), along hierarchy of levels from local community to several urban levels, then national to regional, and potentially global drivers.

The object-oriented design of LAMOS will allow easy implementation of different land use change algorithms. We intend to implement most common algorithms such as those contained in other land use change models including IMAGE 2.0 (land use submodel), HILT (cellular automata), LUCAS (logit regression land-use change function) and so on.

Extensions of LCLUC to Global Change and Sustainable Natural Resources Management

The results of our land use study are being incorporated into integrated assessment plans for Southern Africa, in natural resources management (e.g. in studies in Mozambique), and will be useful in emissions studies under the NASA-led SAFARI 2000 project for Southern Africa (http://safari.gecp.virginia.edu).

Data Sets and Web Access

Climate CD-ROM for some Miombo Countries available at
http://miombo.gecp.virginia.edu/climatecd

Miombo Regional Map for 1990 will soon be available via the miombo web page as well.

Miombo Information Management System: previews of Landsat data holdings (more than 200 scenes, including 35 Landsat 7 scenes) are available via the miombo web page. We are in the process of implementing an online server for the raw and processed band data. Users will be able to preview raw band combinations when the system is fully implemented. We have acquired MrSIDS software for image compression, as well as ER Mapper GIS for this component. The ultimate goal is to allow members of the Miombo Network to download Landsat data for their use from our web site. Those in Southern Africa that can not access data via the internet, can submit their requests and data will be send to them on a CD-ROM.

Meetings Organized or Attended:

Organized Miombo Modeling Workshop, Kamuzu Academy, Kasungu, Malawi, June 14-21, 1998. Funded by START

Organized Miombo Data, Spatial and Integrated Modeling Workshops, Southern Africa, Workshop Report. Funded by the EU through START, and NOAA.

Attended IPCC Integrated Assessment Modeling Workshop, Kadoma, Zimbabwe, November, 1998

Organized NSF US-Mozambique Workshop on Integrated Analysis and Sustainable Natural Resources Management, Maputo, June 7-11, 1999. Funded by NSF, Rockefeller Foundation, Ford Foundation and SG-2000.

Organized Africa Expert Meeting on Global Climate Change. Rabat, Morocco, August 2-5th, 1999; Funded by the IPCC Trust Fund.

Attended Various IPCC Working Group II Third Assessment Report Writing meetings.

Attended UNEP Global Composite Vulnerability Index of Climate Change Workshop, Nairobi, Kenya, October 5-6th, 1999.

Attended Tropical GOFC Workshop, March 15-18th, 1999, Washington, D.C.

Publications

Desanker, P.V. 1999. *A strategy to monitor and model miombo ecosystem transformations: vegetation dynamics, and use/land cover and carbon*. *Report of a Miombo Modeling Workshop*, Kamuzu Academy, Kasungu, Malawi, June 14-21, 1998. START Report No. 4, 1999 (in press).

Desanker, P.V. 1999. *Miombo Data, Spatial and Integrated Modeling Workshops, Southern Africa, Workshop Report*. START Report No. 5, 1999. (http://www.start.org).

Jaiteh, M.S., and P.V. Desanker (submitted). *Comparisons Of Supervised And Unsupervised Classification Of Landsat Tm Data For Miombo Land Cover Mapping*.

Jaiteh, M.S. and P. V. Desanker (submitted) *Computer-Assisted Classification Of Landsat TM Data For Miombo Land Cover Mapping.*

Jaiteh, M.S., P.V. Desanker, and J. Chen. (submitted) *Spatial And Temporal Characteristics Of Landscape Change In The Miombo.*

Desanker, Paul V., Gray Munthali, Leonard Unganai, Kennedy Masamvu and Christopher Justice (2000) Requirements for integrated assessment modelling at the subregional and national

levels in Africa to address climate change and natural resource management. In: *Climate Change for Africa: Science, Technology, Policy and Capacity Building.* Editor: Pak Sum Low (to be published by Kluwer Academic Publishers, April 2000)

Desanker, P.V. and C. Magadza (Coordinating Lead Authors; plus 11 Lead Authors and 13 Contributing Authors). **Africa**. Chapter 10 of the IPCC Working Group II, Third Assessment Report. (to be Published by Cambridge in 2001). (currently in revision, to be submitted for government review in April 2000).

Desanker, P.V (Guest Editor). *Africa and Global Climate Change Special Issue*, Climate Research, (to be published in 2000) (will also contribute a paper on *Land Use and Climate Change in Africa*)

Desanker, P.V., M.S. Jaiteh, S. Walker (submitted to Forest Ecology and Management) *Modeling Forest Carbon in the Miombo Region: Approaches and Initial Results.*

Desanker, P.V. 1999. Miombo Region Climate CD-ROM, CD-Rom Creation Workshop, Harare, Zimbabwe, April 19-23, 1999. START CD-ROM Number 3; October 1999 (http://www.start.org or http://miombo.gecp.virginia.edu/climatecd).

Paul V. Desanker, Malanding S. Jaiteh[2], Dominick Kwesha[3], Manuel Ferrao, Pius Yanda, and Quanfa Zhang[1]. The Miombo Regional Land Cover Map: First Results and Suggestions for a Land Cover Change Monitoring Activity, submitted to Conservation Biology.

Desanker, P. V. and Luisa Santos. 1999. Proceedings of the NSF US-Mozambique Workshop on Integrated Modeling and Sustainable Natural Resources Management, Maputo, Mozambique June 7-11, 1999.

Coupling Land Use, Land-Cover Changes and Ecosystem Processes in Miombo Woodlands

(Report for the period April 1999-November 1999 on
UVA Subcontract under NASA Grant No. NAG5-6384)

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Introduction

Woodlands dominated by trees of the genera *Brachystegia*, *Julbernardia* and *Isoberlinia*, colloquially known as *miombo*, cover about 3 million km^2 of southern central Africa from Zimbabwe to Tanzania. They occur under a seasonal sub-humid climate on the largely infertile soils of the relatively flat African and Post-African (Miocene) geomorphic planation surfaces. Interspersed within these woodlands are broad, largely linear, seasonally wet, grassy depressions, locally called *dambos*, which form the upper parts of the regional drainage network. Together, these woodlands and grasslands constitutes the miombo eco-region, the largest more-or-less contiguous block of deciduous tropical woodlands and dry forests in the world. The region supports upwards of 54 million people, more than 70% of whom live in rural communities, mostly as small-scale commercial or subsistence farmers. Given the infertility of most of the soils, limitations on livestock production due to poor-quality forage and the prevalence of disease, strongly seasonal rainfall with periodic droughts, and a range of social and economic constraints on more productive land-use options, productivity is low and much of the land use extensive rather than intensive. The consequence is widespread conversion of land from its original woodland and grassland land cover to arable land, heavily grazing land, and denuded woodland.

This project is aimed at developing a better understanding of :

- the patterns and causes of change in land use and land cover in miombo ecosystems ;
- the impacts of these changes on the functioning of these ecosystems;
- the potential contribution that these changes in land cover and ecosystem functioning might make to global environmental change; and
- the longer-term consequences of both the changes themselves and the anticipated broader-scale changes in climate on both ecological and socio-economic functioning in the region.

The 3-year study combines remote sensing, ground data collection and ecological modelling to achieve these aims. This report largely covers the research carried out at the Institute of Environmental Studies, University of Zimbabwe, over the period April - November 1999.

Patterns of land cover

Studies of land-cover patterns and attributes have been undertaken at a number of sites. Much of the focus has been on land cover in the communal (mostly subsistence farming) and large-scale commercial farming areas, though earlier work also covered small-scale commercial farming areas, resettlement areas, and a protected area (see previous report). This focus on communal land and large-scale commercial farming areas reflects their importance in areal terms. Together they constitute just under three-quarters of the total available land in Zimbabwe (Table 1). Within agro-ecological zones NR II and III, where miombo is the predominant natural land cover, communal farmland covers almost 31%, and large-scale commercial farms 47%, of the land area (Table 1).

Table 1. Distribution of different land-tenure systems in relation to agro-ecological zones (Natural Regions) in Zimbabwe. The Natural Regions are classified from the least constrained areas biophysically (NR I) to the most constrained, areas with low rainfall (<500 mm p.a.) and frequent droughts (NR V). The data show the percent of the area of a Natural Region under each land-tenure category.

	NATURAL REGION						
Land tenure category	I	IIa	IIb	III	IV	V	Total
Communal Land	14.7	23.2	29.5	35.2	48.6	41.9	40.1
Large scale commercial farming	40.8	66.8	46.5	36.9	19.9	32.9	33.0
Small-scale commercial farming	0.7	4.0	4.3	7.5	3.1	0.8	3.6
Resettlement land (post-1980)	7.1	5.0	17.9	11.2	6.9	3.8	7.4
National parks and safari areas	12.4	0.2	0.1	6.6	16.1	16.0	11.6
State forests	23.1	0.0	0.9	1.5	4.3	0.6	2.6
State land (other)	0.0	0.6	0.2	0.2	0.7	0.2	0.4
Urban land	1.1	0.0	0.3	0.6	0.4	0.1	0.4
Total	1.7	10.8	4.9	20.2	39.9	22.4	100.0
Area (km^2)	6,712	41,772	18,819	78,143	154,088	86,480	386,014

Estimates of land cover in five communal farming areas and five large-scale commercial farming areas, selected primarily for their comparability in terms of geographic location, climate, geology and soils (though the last two were often factors used in the unequal allocation of land during the colonial era), were derived from supervised classification of Landsat-5 bands 1 - 5 and 7 from images taken in September and October 1995. The images were spectrally enhanced using the Decorrelation Stretch procedure in Erdas Imagine® prior to classification. Relatively broad land-cover classes were used. Even then, the predominant pattern was an extremely fine-grained mosaic of different land-cover types that reflected the inherent heterogeneity of the landscapes and the fine-scaled pattern of land use. To make the results more tractable and amenable to subsequent analyses, the spectrally-enhanced images were re-classified after they had been subject to an unweighted low-pass (3x3) filter.

The results show substantial differences in land cover between the communal and commercial farming areas (Figure 1, Table 2). On average, communal lands are more extensively cultivated (31% of the area transformed to cultivated land) and have much less woodland cover (25% of the communal land) than the large-scale commercial farming areas (20% cultivated land and 45% woodland cover types). Some of the woodland in communal land has been converted to bushland through the removal of most of the canopy trees. This is reflected in the slightly higher percentage of bushland in the communal farming areas (13%) than in the commercial farming areas (9%). Except for the 'other' land-cover category, differences in the proportions of the other land cover types do not differ substantially between these two land tenure systems. 'Other' land covers include rocky outcrops, water bodies, fire scars and shadows in hills, and is much higher in communal areas (11%) than in commercial farming areas (3%). This largely reflects the greater number of hills and rocky outcrops in communal land, a feature that lowers the agricultural suitability of these landscapes and limits the extent of land-cover transformation, but which also tends to preserve some woodland resources on which communal residents so depend.

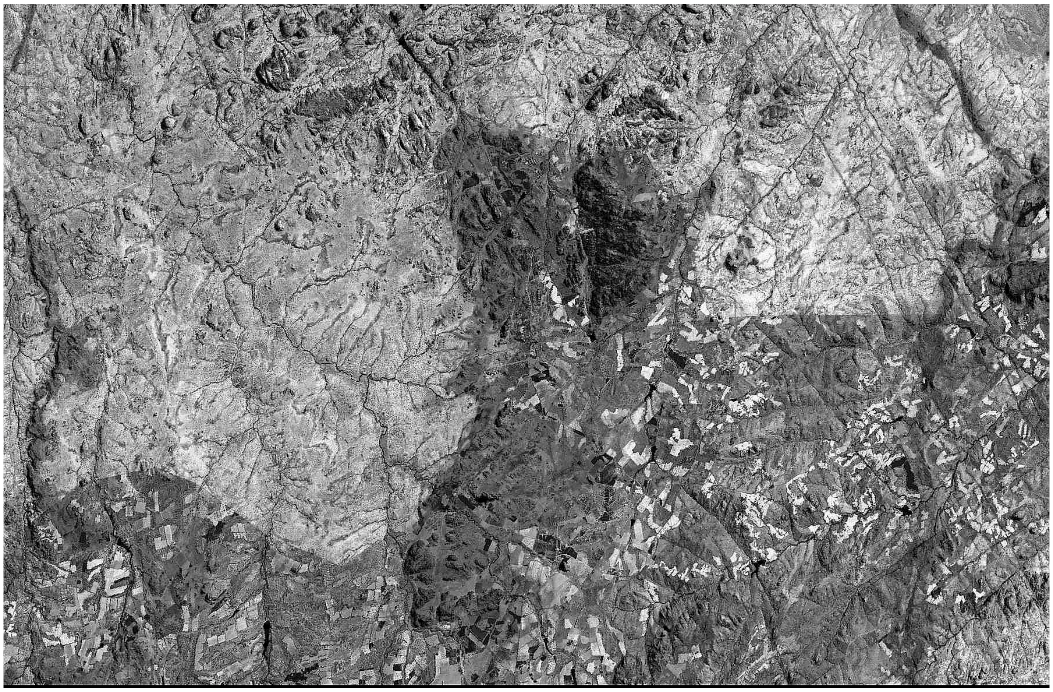


Figure 1. Boundary between Mangwende communal land (upper half of image) and the Virginia large-scale commercial farming area (lower half of image), Mashonaland East, Zimbabwe, showing the contrast between the more densely wooded commercial farming area (darker tones) and the relatively denuded land cover of the communal area (lighter tones). The lightest tones represent cultivated lands. Picture derived from spectrally-enhanced Landsat 5 image LT51690729524510 taken on 2 September 1995.

Table 2. Average per cent of survey areas under different land-cover types in five communal and five large-scale commercial farming areas. Data derived from supervised and semi-supervised classification of Landsat TM images taken in September and October 1995, augmented by aerial photographs taken in August 1995.

	Communal farming areas [1]		**Commercial farming areas** [2]	
Land-cover category	**Average %** [3]	**(range)**	**Average %** [3]	**(range)**
Woodland (>10% tree canopy cover; trees >2 m tall)	24.8	(7.6 – 42.7)	45.3	(30.5 – 72.3)
Grassland/wooded grassland (<10% tree canopy cover)	19.5	(3.5 – 35.7)	22.8	(9.0 – 47.3)
Shrubland (>10% tree canopy cover; trees <2 m tall)	12.9	(8.2 – 24.0)	8.8	(2.8 – 14.4)
Cultivated land	31.4	(11.3 – 39.6)	19.7	(9.8 – 29.4)
Dryland crops	*30.8*	*(10.9 – 39.6)*	*17.5*	*(9.1 – 29.4)*
Irrigated crops	*0.0*	*(0.0 – 0.1)*	*0.7*	*(0.0 – 2.0)*
Eucalyptus plantations	*0.5*	*(0.0 – 1.3)*	*1.5*	*(0.0 – 3.4)*
Other (water bodies, fire scars, bare rock and soil, shadows)	11.3	(3.1 – 14.8)	3.4	(0.4 – 7.5)

[1] Mangwende, Mutoko and Chivi communal areas (total area surveyed: 1925 km^2)
[2] Virginia, Arcturus and Shamva commercial farming areas (total area surveyed: 1785 km^2)
[3] Area-weighted average

The difference in extent of cultivated land in communal and commercial farming areas has led to perceptions that much of the land on commercial farms is under-utilised, prompting calls for land redistribution not only to correct the historical imbalances in land allocation but also to make fuller use of the country's resources to promote development. The single most important reason for clearing woodlands is the need for land for cultivation. The level of deforestation therefore increases with increasing rural population density, particularly in the more densely settled communal farming areas (Figure 2). Some of the most dramatic recent declines in woodland cover are currently to be seen in resettlement areas (Grundy *et al.*, 1993) and in the more remote communal areas that are currently being spontaneously settled (WWF, 1997).

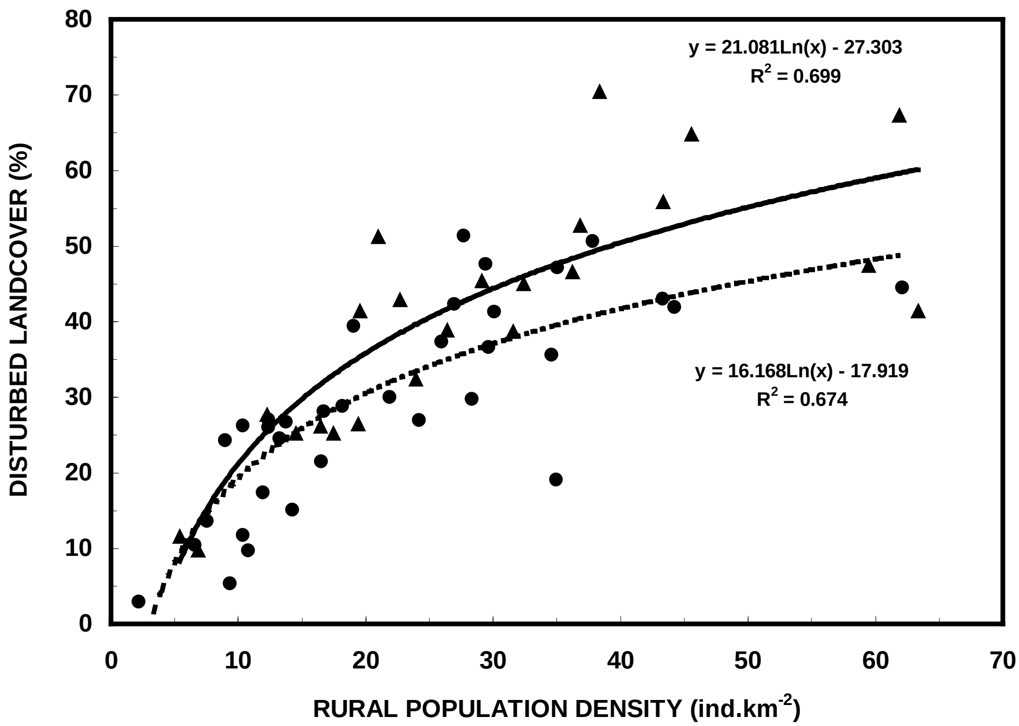


Figure 2. Relationship between population density and percentage of disturbed land (comprising mainly cultivated and other deforested or denuded land) in 57 administrative districts in Zimbabwe, 1992. The data are divided into those districts in which communal land makes up 50% or more of the district (solid line and triangles), and those in which it comprises less (dashed line and dots). Data on percentage of disturbed land derived from a digital version of the Zimbabwe Forestry Commission's woody cover map (Zimbabwe Forestry Commission, 1996), while data on human population densities in the 57 administrative districts comes from the Zimbabwe 1992 Population Census (Central Statistics Office, 1994).

Analyses of landscape pattern have been carried out on two 236 km^2 subsets of each of the classified smoothed images for a communal land (Mangwende) and a large-scale commercial farming area (Virginia ICA). Patterns were analysed using the programme FRAGSTATS (McGarigal and Marks, 1995). At a landscape level, there was little difference among the sites in terms of selected landscape attributes (Table 3). With a average density of 34-36 patches per 100 ha, the landscapes of both land tenure types are highly fragmented. Mean patch size was about 3 ha but there is huge variation in this as shown by the large coefficients of variation. This reflects the strongly skewed distribution of patch sizes in all land-cover classes at each site.

Table 3. Selected landscape attributes for two communal land sites (Musami A, B) and two large-scale commercial farming areas (Virginia A, B) as determined using the programme FRAGSTATS (McGarigal and Marks, 1995).

	Musami		Virginia	
Landscape attribute	A	B	A	B
Total area (ha)	23593	23593	23593	23593
Number of patches	8365	8064	7927	8180
Mean patch size (ha)	2.8	2.9	3.0	2.9
Patch size CV (%)	1399	820	1645	1940
Landscape shape index	54.4	57.2	52.1	56.9
Double log fractal dimension	1.38	1.38	1.40	1.40
Mean nearest neighbour distance (m)	114	97	100	98
Shannon's diversity index	1.64	1.78	1.85	1.74
Interspersion and juxtaposition index (%)	64.0	66.1	70.2	63.0
Contagion index (%)	50.9	45.4	46.9	48.6

Differences among the sites, particularly between the communal land and commercial farmland sites, is more apparent at the level of individual land-cover classes. Table 4 shows data for selected attributes of the six most widespread land-cover types. The percent of landscape covered by open woodland, and the proportion of that area covered by the largest open woodland patch, is substantially greater in the commercial farming areas than in the two communal land sites. The converse applies in the case of cultivated land. The density of patches of cultivated land are somewhat greater in the communal lands, as would be expected, given the greater proportion of land under agriculture in these areas. Substantial differences in the landscape shape indices occur, with the values being higher in those land-cover classes and sites where the particular land-cover type is widespread. Not surprisingly, mean nearest neighbour distance is inversely related to patch density. The indices of interspersion and juxtaposition are broadly similar across most land-cover classes and sites, though they are lower for all closed woodland sites.

A detailed analysis of patches was undertaken only for the combined (open plus closed) woodland classes and cultivated land. Within the commercial farming areas 32-39% of woodland patches were larger than 1 ha in area, compared to 25-27% in the communal lands. The converse was true for cultivated lands. In all cases, however, the distribution of patch sizes was strongly skewed.

The spatial distribution and size of both woodland and cultivated land patches in the two land-tenure systems is illustrated in Figures 3 and 4. These clearly illustrate the contrasting nature of woodland and cultivated land cover in the two systems, though in both cases the distribution of patch sizes is strongly negatively skewed, with most patches being <1 ha in extent. In the case of the commercial farming areas, this may reflect misclassification of small clusters of pixels, tending to break up what are in reality fairly large fields (although wooded termitaria are left scattered across these fields, the probably source of confusion in consistently classifying pixels containing these features).

Table 4. Selected land-cover class attributes for two communal land sites (Musami A, B) and two large-scale commercial farming areas (Virginia A, B) as determined using the programme FRAGSTATS (McGarigal and Marks, 1995). The area of each study site was 236 km^2.

Land-cover class			% of landscape	largest patch index (%)	Patch density ($100m^{-1}$)	Mean patch size (ha)	Patch size CV (%)	Landscape shape index	Double log fractal dimension	Mean nearest neighbour distance (m)	Interspersion/ juxtaposition index
Open woodland	Musami	A	8.5	1.4	3.6	2.4	608	11.28	1.37	112	71.7
		B	9.6	3.6	2.2	4.4	928	8.56	1.35	131	78.2
	Virginia	A	32.7	15.5	4.0	8.2	1489	23.61	1.40	67	73.9
		B	38.5	19.6	3.6	10.6	1599	26.88	1.39	64	64.0
Closed woodland	Musami	A	0.9	0.1	0.9	1.0	267	2.48	1.32	298	40.1
		B	0.1	<<0.1	0.2	0.5	140	1.27	1.32	498	36.3
	Virginia	A	2.1	0.3	1.4	1.5	347	4.65	1.46	171	41.3
		B	0.2	<<0.1	0.4	0.5	145	1.56	1.46	421	47.3
Bushclump savanna	Musami	A	26.4	2.3	6.1	4.3	600	27.82	1.41	63	61.2
		B	14.0	1.7	6.7	2.1	654	19.18	1.39	78	63.7
	Virginia	A	7.4	0.5	5.5	1.4	362	13.27	1.41	88	63.8
		B	13.1	2.3	6.3	2.1	726	19.57	1.42	75	54.4
Grassland/fallow mosaic	Musami	A	0.6	0.1	1.2	0.5	217	2.48	1.35	264	59.2
		B	2.9	0.1	3.1	1.0	195	6.46	1.35	138	46.5
	Virginia	A	25.3	6.4	2.6	9.7	879	17.92	1.36	95	52.2
		B	13.9	1.6	4.7	2.9	503	16.43	1.34	89	42.0
Cultivated land	Musami	A	41.5	9.8	4.8	8.7	1174	29.97	1.40	54	57.4
		B	20.4	4.5	7.3	2.8	952	25.10	1.38	65	65.3
	Virginia	A	10.3	1.4	3.9	2.7	490	12.49	1.37	76	79.1
		B	6.7	0.2	4.0	1.7	255	10.68	1.35	77	73.2
Dambo grassland	Musami	A	6.4	0.3	4.1	1.6	301	10.42	1.36	103	69.9
		B	23.1	2.1	4.8	4.8	529	26.25	1.43	62	72.8
	Virginia	A	12.3	0.9	7.7	1.6	550	19.69	1.43	66	64.5
		B	19.0	1.0	9.1	2.1	458	28.80	1.45	60	64.7

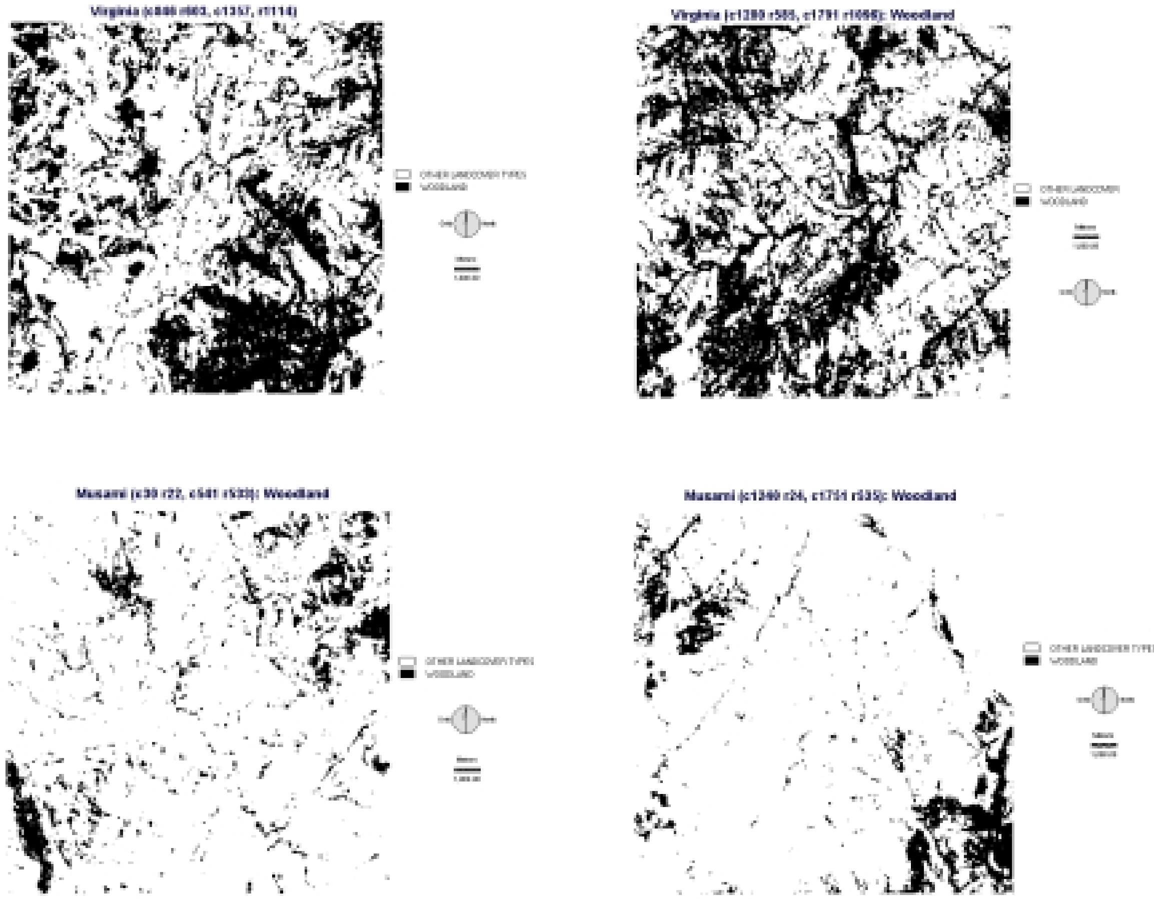


Figure 3. Distribution of woodland patches in two commercial farming areas (Virginia) and communal land areas (Musami), showing the much reduced woodland cover in the communal lands. This reflects the pressure to convert woodland (and other suitable natural land-cover types) to cultivated land. The relatively large patches of woodland in the communal areas are located in hilly terrain where the land is unsuitable for cultivation.

The distance to woodland at these sites was calculated using the DISTANCE function in Idrisi®. In the commercial farming areas, almost all the area lies within 500 m of woodland, whereas only 72-90% of the area in communal land is so situated. People travelling to collect natural products from woodland would have to travel further, on average, than people living in the better wooded commercial farming areas. Moreover, many of the woodland patches in the communal lands are small and relatively isolated (average size: 3.4 ha; mean nearest neighbour distance: 133 m), compared to those in the commercial farming areas (average size: 10.1 ha; mean nearest neighbour distance: 66 m). This fragmentation and isolation of woodland is likely to have a negative effect on biodiversity, as well as on the abundance and availability of non-timber forest products on which rural people depend, particularly during times of hardship (Campbell *et al.*, in press). This dependence is greater amongst the poorer members of the community.

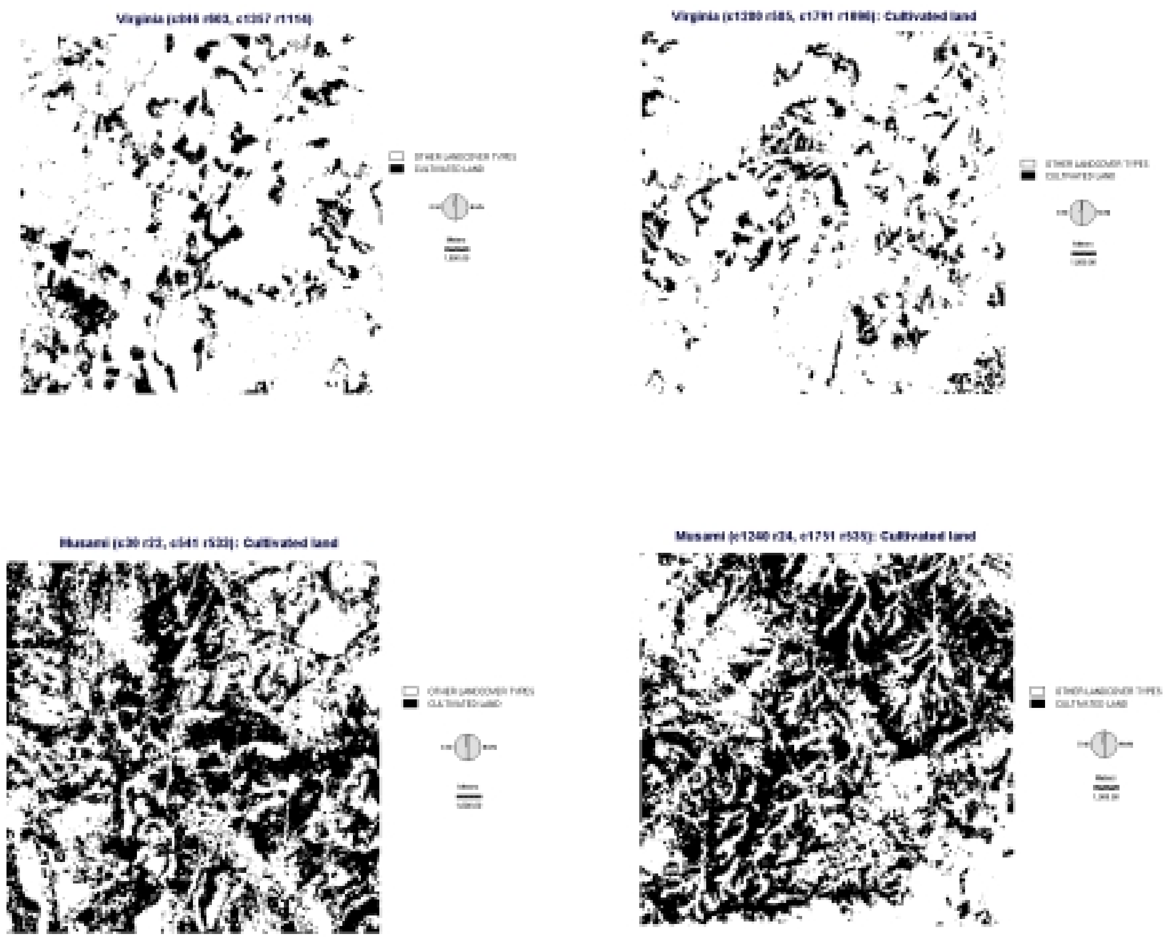


Figure 4. Distribution of patches of cultivated land in two commercial farming areas (Virginia) and communal land areas (Musami), showing the much greater area under cultivation in the communal lands.

Dynamics of land-cover change

Campbell *et al.* (in press) have developed a conceptual model of land-use change in Zimbabwe that considers the impacts of various national policies of the livelihood strategies of people living in communal farming areas. The analysis further considers how changes in these livelihood strategies in turn influence various demographic, social and economic processes affecting woodlands, for instance, land pressures due to population growth, degree of commercialisation of woodland products, and the relative value of agricultural and woodland activities. Three drivers of change in the model are impacted directly by policies - land pressures, rural-urban linkages, and the recent upsurge in tourism. Two other drivers, drought and the increasing incidence of AIDS, are only indirectly and loosely connected to policy.

The conceptual box-and-arrow model has helped to specify the connections among the different elements of the complex ecological-social-economic system prevailing in the communal lands of Zimbabwe and its links to urban areas. Relationships among different components have been clarified and the current gaps in knowledge identified. The model, however, is only an initial step. A simulation model is currently being developed using STELLA, a high-level modelling package, to analyse the dynamics of these woodland-based rural livelihood systems in greater depth, to examine these linkages in more detail, and to explore scenarios of change in the use and management of these woodland resources and their implications for land-use change (Frost, Luckert, Campbell and De Jong, in prep.).

Another model, to examine interactions among tree growth, grass production, grazing, fire and harvesting, so as to better understand the longer-term dynamics of miombo woodlands under different kinds and intensities of use has been developed by Gambiza *et al.* (in press). The model forms the core of a broader ecological-economic model of the people-woodland interactions in miombo and Kalahari sand woodlands (papers in press in *Ecological Economics*). In particular, the model was developed to investigate the effects of removing canopy trees on woodland structure, grass fuel loads, and fire frequency and intensity, as well as the impacts of changing fire frequency and intensity on woodland structure. The effect of cattle grazing on fuel loads, fire frequency and intensity, and woodland structure was also investigated.

The model showed that over time intensive timber-harvesting, without cattle grazing, resulted in higher fuel loads, more frequent hotter fires, and reduced woody regeneration (Figures 5, 6). Even slight increases in cattle stocking rates, however, significantly reduced fuel loads, fire frequencies and intensities, and improved tree regeneration. Under these circumstances the vegetation becomes dominated by numerous, relatively small, fire-suppressed woody plants that are unable to escape the ravages of frequent fires. This is called the 'fire trap' (Bell, 1984).

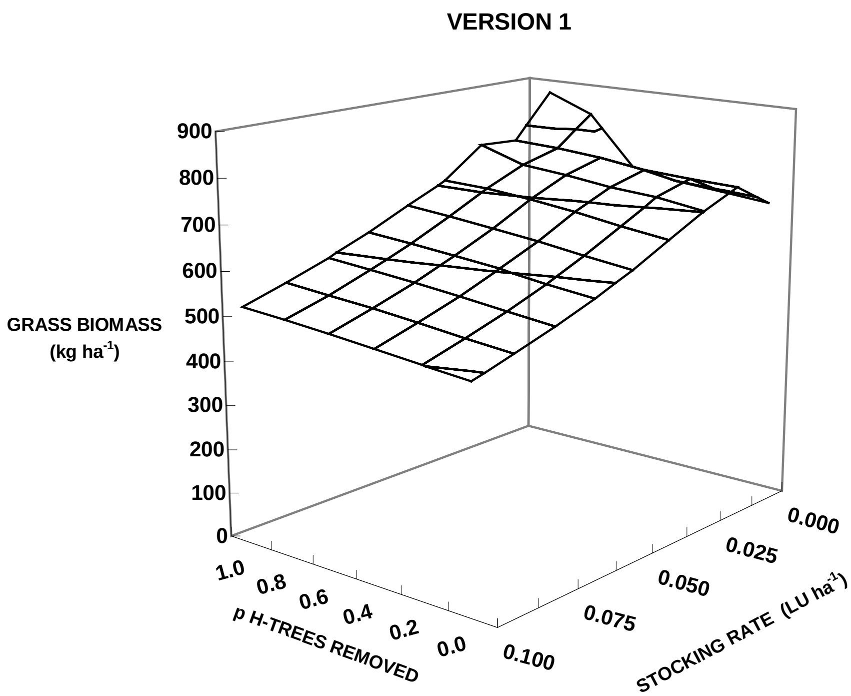
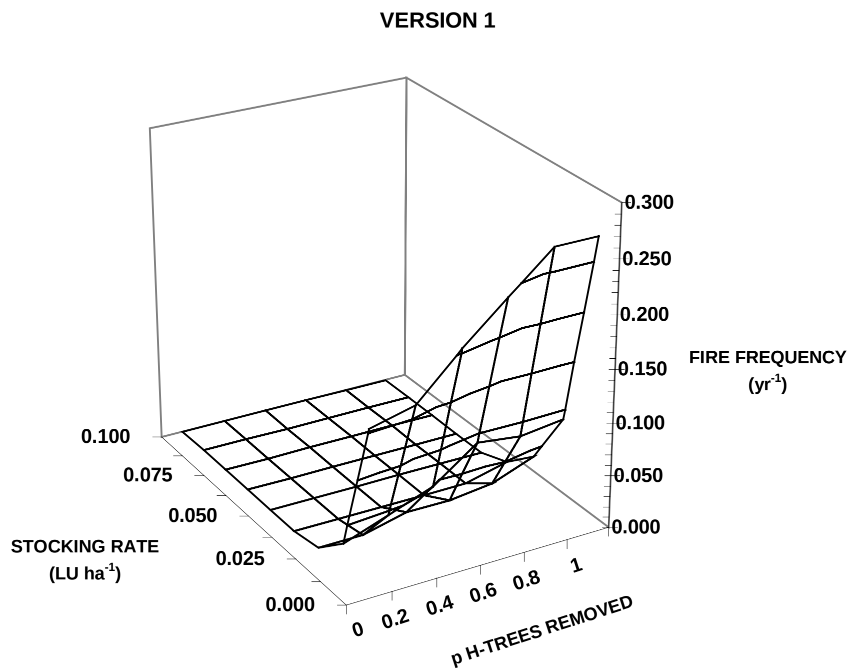


Figure 5. The mean grass biomass (kg ha^{-1}) under different cattle stocking rates and levels of tree removal. The mean values were calculated for the whole 200 years of the simulation. Version 1 of the model represents a scenario of presumed normal tree growth rates, in contrast to Version 2 (not shown) in which growth rates were halved. The cutting cycle was set at 40 years. ‘p h-tree removed’ refers to the proportion of harvestable trees (>35 cm DBH) harvested at each cutting cycle.



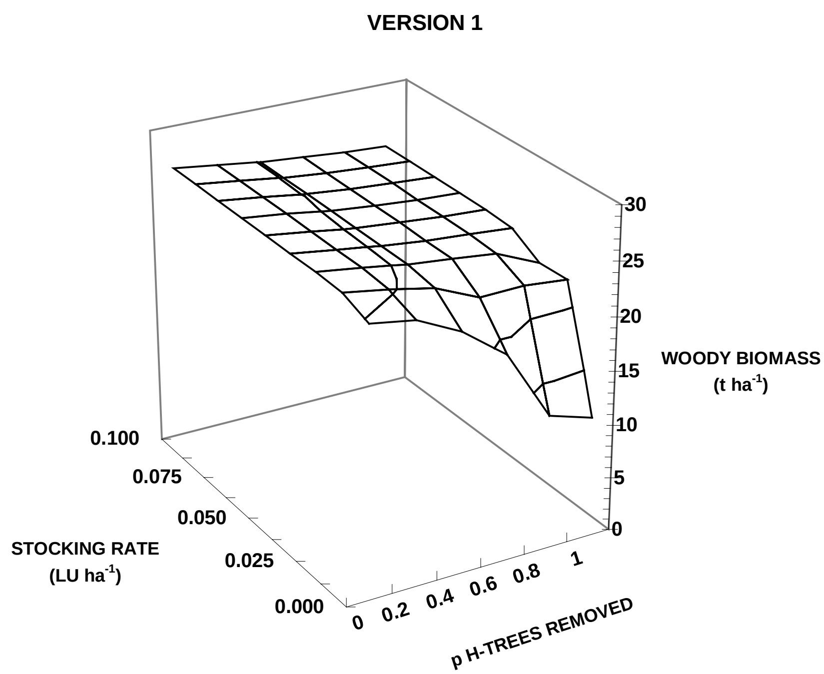


Figure 6. Opening up of woodland canopy results in increased grass growth, greater fuel loads, and more frequent, hotter fires (a), leading to suppression of woody plant regrowth and lower biomass – the 'fire trap' (b). Heavy grazing by livestock reduces the amount of fuel for fires, thereby lowering fire frequencies and intensities. Results from Version 1 of the model. 'p h-trees removed' refers to the proportion of harvestable trees removed in each 40-year cutting cycle.

The model has been developed in two versions: Version 1, parameterised with presumed normal growth rates for miombo trees, and Version 2, in which the growth rates were halved. Slowing the growth rates of the trees resulted in greater grass production over time, higher fuel loads, more frequent and intense fires, and an intensified 'fire trap' for woody plants (cf. Figure 6a).

Conclusion

Progress to date has been made on improving the basis for supervised classification of Landsat imagery, using a combination of analysis of aerial photography and geo-referenced ground-based observations to classify training sites and evaluate the validity of the classification. Progress has also been made in developing integrated socio-economic and ecological models of land use and land-use change in these ecosystems, and in understanding the impacts of these on land cover. Much less progress has been made in determining change over time, primarily due to difficulties in obtaining the requisite Landsat imagery from the University of Virginia. Unless this matter can be resolved, there will be little progress in this field, though provision has been made to use time-series of aerial photographs of selected areas. This solution is not optimal, however, because of differences in scale and quality of the photographs taken over time, and the much more labour intensive nature of the work.

A list of papers published or in press during 1999 is attached (Appendix 1), together with a list of meetings and workshops attended during the year (Appendix 2). This latter list excludes meetings and workshops arranged within the framework of research programmes run by the Institute of Environmental Studies.

References

Bell, R.H.V. 1984. Notes on elephant-woodland interaction. In: Cumming D.H.M. and Jackson, P. (eds) Status and Conservation of Africa’s Elephants and Rhinos, IUCN, Gland.

Campbell, B., Frost, P., Goebel, A., Standa-Gunda, W., Mukamuri, B., and Veeman, M. (in press). A conceptual model of woodland use and change in Zimbabwe. *ITC Journal (Special Issue)*

Gambiza, J., Bond, W., Frost, P.G.H., and Higgins, S. (in press). A simulation model of miombo woodland dynamics under different management regimes. *Ecological Economics*

Grundy, I.M. Campbell, B.M., Balebereho, S., Cunliffe, R., Tafangenyasha, C., Ferguson, R. and Parry, D. 1993. Availability and use of trees in Mutanda resettlement area, Zimbabwe. *Forest Ecology and Management* 56:243-266.

McGarigal, K. and Marks, B.J. (1995). FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. Gen. Tech. Rep. PNW-GTR-351. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon.

WWF. 1997. *Land Use Changes, Wildlife Conservation and Utilisation, and the Sustainability of Agro-ecosystems in the Zambezi Valley*. Final Report to the European Commission, Project B7-5040/93/06. WWF Regional Office, Harare, Zimbabwe.

Appendix 1

Papers published or in press during 1999

1. **Frost, P.G.H.** (1999). Fire in southern African woodlands: origins, impacts, effects, and control. In: Proceedings of an FAO Meeting on Public Policies Affecting Forest Fires, *FAO Forestry Paper* **138**, 181-205.

2. **Frost, P.G.H.** (1999). Community-based management of fire: lessons from the Western Province in Zambia. In: Proceedings of an FAO Meeting on Public Policies Affecting Forest Fires, *FAO Forestry Paper* **138**, 341-351

3. Chirara, C., **Frost, P.G.H.**, and Gwarazimba, V.E. 1999. Grass defoliation affecting survival and growth of seedlings of Acacia karroo, an encroaching species in southwestern Zimbabwe. *African Journal of Range & Forage Science* **15**, 41-47.

4. **Frost, P.G.H.** and Mandondo, A. (1999). Emerging issues in natural resource management in semi-arid production systems. *IES Working Paper* **12**, 18 pp.

5. Campbell, B., **Frost, P.**, Goebel, A., Standa-Gunda, W., Mukamuri, B., and Veeman, M. (in press). A conceptual model of woodland use and change in Zimbabwe. *ITC Journal (Special Issue)*

6. Gambiza, J., Bond, W., **Frost, P.G.H.**, and Higgins, S. (in press). A simulation model of miombo woodland dynamics under different management regimes. *Ecological Economics*.

7. Campbell, B., Chuma, E., **Frost, P.**, Mandondo, A., and Sithole, B. (in press). Interdisciplinary challenges for environmental researchers in rural farming systems. *Proceedings of 3rd Zimbabwe Science and Technology Symposium.* Harare, August 1999.

8. Sithole, B. and **Frost, P.** (in press) Appropriate social units of analysis in the CAMPFIRE program in Zimbabwe. In: Proceedings of an IUCN workshop on *Resolving the Conundrum of Scale in Adaptive Management – Households to Larger Landscapes*, 18-20 June, Ottowa, Canada.

9. Campbell, B., Sithole, B., and **Frost, P.** (in press). Villagers and scientists Technical Comment on Getz *et al.* Sustaining natural and human capital: villagers and scientists. *Science*.

Appendix 2

Meetings attended and papers presented 1999

1. First Lead Authors' Meeting *Intergovernmental Panel on Climate Change: Special Report on land-Use Change and Forestry*. World Meteorological Organization, Geneva, Switzerland, 11-13 January 1999.

2. Training Workshop on *National Greenhouse Gas Emissions Inventories*. United Nations Environment Programme, Nairobi, Kenya, 19-21 January 1999. (Served as a resource person for the workshop and presented an overview of the IPCC Revised 1996 Guidelines on National Greenhouse Gas Emissions Inventories in the Land-Use Change and Forestry Sector.)

3. Workshop on *Sustainable Development and Natural Resource Management in Southern Zimbabwe*, Oasis Hotel, Harare, Zimbabwe, 10 March 1999

4. Workshop on *Ecology and Management of Fire in Miombo Ecosystems*. Matopos, Zimbabwe, 19-23 April 1999 (Organised the workshop and presented papers on (1) *Vegetation Changes in* Burkea-Terminalia *Woodland at Matopos, Zimbabwe, following 46 Years of Experimental Burning*; (2) *Regrowth of* Burkea africana *and* Terminalia sericea *following Late Dry Season Fires Burnt at Different Frequencies on Matopos Research Station, Zimbabwe*; and (3) *Community-Based Management of Fire: Lessons from the Western Province in Zambia*.)

8. Second Lead Authors' Meeting *Intergovernmental Panel on Climate Change: Special Report on land-Use Change and Forestry*. World Bank, Washington DC, USA, 28-30 April 1999.

9. NASA Workshop *Land Cover and Land Use Change*, Airlie, Virginia, USA, 18-21 May 1999 (Presented a report on the Matopos Fire Ecology and Management meeting – see 4 above. Dr Desanker presented progress report on work done to date.)

10. CASS/IUCN Short Course on *Human and Social Perspectives in Natural Resource Management*, Courtney Hotel, Harare, 10 June 1999 (gave a talk on *Networks as Organisations for Natural Resource Management*)

11. Agritex/University of Queensland/CASS/Campfire Association/IES First National Technical Workshop *Enhanced Resource-Use Planning for Tropical Woodland Agroecosystems*, Oasis Hotel, Harare, 28 June – 1 July 1999 (served as facilitator for the workshop).

12. World Forest Forum Symposium on *Forests and Atmosphere-Water-Soil*, Soltau, Germany, 2-5 July 1999 (presented paper on *Forests in Africa: options for sustainable development and climate-change mitigation* at a workshop on *Forests after the Kyoto Protocol – their potential role as sources and sinks of trace gases, particularly carbon dioxide* held at this symposium).

13. Save Valley Conservancy/WWF Workshop on *Research and Monitoring Priorities in the Save Valley Conservancy*, Levanga, Save Valley Conservancy, 24-25 August 1999.

14. IIED/ECCM/University of Aberdeen/EcoSecurities Workshop on *Carbon, Forests and Rural Livelihoods*, 20-21 September 1999 (gave a country overview of issues related to carbon-offset initiatives and enhancement of rural livelihoods).

15. BAHC/UNEP/AMCEN Workshop on *Sustainability of Freshwater Resources in Africa*, Nairobi, 26-29 October 1999 (gave a stage-setting presentation on *Integrated Land and Water Management*)

16. GOFC Workshop on *Forest Fire Monitoring and Mapping*, JRC/SAI Ispra, Italy, November 3-5, 1999. (contributed a paper on *Information Requirements of Policy and Decision Makers*; served as co-chair and rapporteur of working group on *Synthesis Initiatives*.)

P.G.H. Frost
December 1999