Norwegian University of Life Sciences
Faculty of Environmental Sciences
and Natural Resource Management

Philosophiae Doctor (PhD)
Thesis 2019:51

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Ås (2019)

Thesis number 2019:51
ISSN 1894-6402
ISBN 978-82-575-1610-9

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DEDICATION

This Doctoral Thesis is dedicated to my lovely mum **Amokile A.H.M. Kyengula** who taught me how to read and write at home and when I started my education journey in standard one at Lusinga Primary School, to my late Grandfather Andrea Matesu Kyengula (R.I.P), to my late Father Zabron Yohana Nyamoga (R.I.P), to my wife Rosemary and daughters Glory, Genevieve & Gabriella. It is difficult to imagine my life at this point without my mum, she has played multiple roles in my life and she is so wonderful. She sacrificed many things to ensure that I got all I needed for my school. I cannot thank her enough but she will remain a special woman of my life forever. Genevieve and Gabriella missed my time, care and love as Father in their early stages of life. Despite joining me in Ås – Norway, they still struggled because of spending most of my time in the office for academic activities hence making my wife Rosemary always busy with them in my absence. I should confess that Rosemary did a very good job.

BI. AMOKILE ANDREA MATESU KYENGULA

Ndikhokholeemya hiii Ouve Mama khwa khouva biila ouve isiinu syee siiva siinge

PREFACE

Aristotle and W. K. Clifford once said *"We are what we repeatedly do & excellence then is not an act but a habit"* and *"It is wrong always, everywhere and for everyone, to believe anything upon insufficient evidences"*. The four years I spent working with Prof. Solberg as my Main Supervisor in this PhD has taught me enough lessons in what it means to be a researcher. The different moments experienced will endure in my memory throughout the remaining time of my life.

I first thank the Almighty GOD for everything. I am very grateful to Professor Birger Solberg for his wonderful mentorship and trainings making me understand not only how to design and complete a research task and write research articles, but also what distinguish research from other activities. Prof. Solberg has been so patient in providing guidance, enthusiastic encouragements and useful critiques throughout this work. I express my profound gratitude to Prof. Yonika Ngaga and Prof. Rodgers Malimbwi for their continuous comments and being very instrumental in getting the necessary official NAFORMA data from the Ministry of Natural Resources and Tourism. I thank Associate Professor Greg Latta for hosting me at Oregon State University in Corvallis and for all help in formulating, programming and implementing the *TanzFor* Model. I acknowledge the contributions and key roles played by Associate Professor Dr. Hanne K. Sjølie who introduced me to the GAMs language and worked with me from scratch. I thank Professor Tron H. Eid for his assistance at the beginning and throughout my PhD and for advices regarding using the NAFORMA plot data, and I thank Dr. E. Mugasha for providing NAFORMA plot simulations. I also thank Professor Samuel Adaramola for endless valuable moral support.

I am indebted by the Government of Norway through the Higher Education Loan Board (Lånekassen) for funding my PhD through the Quota Scheme Scholarship and the Department of Ecology and Natural Resources Management (INA) at the Norwegian University of Life Sciences (NMBU) for providing extra funding for the field works in Tanzania. I thank the Government of Tanzania and Sokoine University of Agriculture in particular for granting the study leave and research permit to conduct my data collection in Tanzania. I thank the managerial Team at the Faculty of Environmental Sciences and Natural Resource Management - Prof. Sjur Baardsen, Dr. Ågot Aakra, Mette Solsvik, Ole Wiggo, Kari Margrete Thue, Stig Danielsen, Gunnar Jensen, Karen Dagny Johnsen, Vivian Boodhun and Grethe Delbeck who have always been very cooperative and helpful in handling all the administrative matters during my PhD studies at MINA. Dr. Beatrice Tarimo is appreciated for assisting me in making the study site maps.

I am very grateful to Mr. M. Kilongo (Director of Utilization), Mr. Chamuya, Mr. Mlowe, Mr. Msuya, Mr. Maggid, Mrs M. Mrutu, Mrs. Mujillah and Brighton Kamugisha from Tanzania Forest Services Agency (TFS) in the Ministry of Natural Resources and Tourism for their welcoming faces, kindness and assistance during data acquisition. Special appreciation to Mr. E. Kayange from TFS-Moshi for being very royal and professional while driving me in Kilimanjaro Region. It is impossible to mention everyone but I extend my gratitude to all

Region/District TFS Forest Officers, TRA Officers – Dar es Salaam Head Quarter, Ward and Village Executive Officers, Sawmills owners, Mgololo Paper Mill (MPM) workers, TANWAT staffs and all other respondents (appendix 2) for providing the information I needed.

I thank my field assistants Mr. R. Okick and Mr. B. Elisafi, master students Ms. W. Nura and S. Tatsumi for helping in data collection. Prof. Abdallah have been very helpful by supervising the master students and for handling administrative issues. I thank all the people at the International Students Center (SIT) for taking care of all the Lånekassen administrative and logistical issues during my four years of studies. I specifically thank Mrs. Vilma Veronica Bischof and Mrs. Tendai Chella Bengtsson for tirelessly responding to so many emails, phone calls and questions. To all my Tanzanian friends in Ås (Mr. Albin Tenga & his Family, Grace, Helen, Isaya, Neema, Ernest, Severin, Deo, Zabron, Scontina, Esther, Aziza, Wema, Mwalubadu, Alice & Thomas), your continuous moral support was great and my fellow PhD Students (Walid, Rafal, Victor, Daud, Solrun, Kaja, Erick, Yennie, Nikoline, Denis, Knut, Pablo, Mahdieh, Ruben, Niels, Silk, Yi-kuang, Hannah, Eirik, Ellen, Marte, Lazarus, Dawit, Miguel, Franz, David, Thomas, Fredrick, Mari, Monica, Mengesteab, Mekdes and Kristel van) and all IBF/Evangelsalen members (Pastor Mats, Jeevan, Mary, Sara, Munyaka, Lucy, Tomiwa, Bodil, Martha, Doreen, Mona, Mussie, Peter, Dorcas, Magrethe, Tina and Taiwo), you all played a big role during my PhD. I appreciate the companion from other friends in Ås – Linda, Charles, Ritha, Svein, Davie, Casandra, Karolina, Irene, Salma and Yousif. I am grateful to Rafal for the time we spent together at Technical University of Denmark (DTU) and Oregon State University during our PhD studies. To Kari Solberg, Liv Ellingsen and Sylvi Haldorsen, you were my mothers in Norway and your kindness, love and welcoming lifestyles will be remembered in my heart forever. *It is hard to mention everyone here but understand that your contributions into this PhD work are highly valued and appreciated.*

Finally, to my wife Rosemary and our daughters (Glory, Genevieve and Gabriella), thank you for handling and managing all the stresses, tensions and frustrations during my PhD studies. This PhD is the outcome of your love, tolerance and supports both morally and materially. **GOD bless you all**.

Isaiah 55: 8 – 9

For my thoughts are not your thoughts, neither are your ways my ways, declares the Lord. For as the heavens are higher than the earth, so are my ways higher than your ways, and my thoughts higher than your thoughts

Greyson Zabron Nyamoga
ÅS-NMBU
May, 2019

LIST OF ACRONYMS

DOVAP	Dodoma Village Afforestation Project
EAM	Eastern Arc Mountain
FAO	United Nations Food and Agriculture Organization
GHGs	Greenhouse Gases
Ha	Hectares
HADO	Hifadhi Ardhi Dodoma
HASHI	Hifadhi Ardhi Shinyanga
HHS	Household Size
HIAP	Handeni Integrated Agroforestry Project
HIMA	Hifadhi Mazingira
INA	Department of Ecology & Natural Resources Management
KG	Kilogram
LAMP	Land Management Program
LPG	Liquefied Petroleum Gas
MAI	Mean Annual Increment
MINA	Faculty of Environmental Science and Nature Management
MNRT	Ministry of Natural Resources and Tourism
MJ	Mega Joules
MJUMITA	Mtandao wa Jamii wa Usimamizi wa Misitu Tanzania (Tanzania Community Forest Network)
NAFORMA	National Forestry Resources Monitoring and Assessment
NBS	National Bureau of Statistics
NFI	National Forest Inventory
NMBU	Norwegian University of Life Sciences
NTFP	Non-Timber Forest Products
PCC	Per-Capita Charcoal Consumption
PES	Payment for Environmental System
PhD	Philosophiae Doctor
SECAP	Soil Erosion Control and Agroforestry Project
SUA	Sokoine University of Agriculture
TaTEDO	Tanzania Traditional Energy Development & Environment Organization
TRA	Tanzania Revenue Authority
TFS	Tanzania Forest Service Agency
TRAFFIC	The Wildlife Trade Monitoring Network
Tshs	Tanzanian Shillings
URT	United Republic of Tanzania
USD	United States Dollar
WB	World Bank

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LIST OF PAPERS

I. Nyamoga G.Z., Sjølie H.K., Malimbwi R., Ngaga Y.M., Solberg B. (2016). Potentials for Rehabilitating Degraded Land in Tanzania. In: Lal R., Kraybill D., Hansen D., Singh B., Msogoya T., Eik L. (eds) *Climate Change and Multi-Dimensional Sustainability in African Agriculture,* pp 149-170. © Springer, Cham. https://link.springer.com/chapter/10.1007/978-3-319-41238-2_8.

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IV. Latta, G., Nyamoga, G.Z., Sjølie, S.K., Ngaga, Y.M., Malimbwi, R., Solberg, B., (2019). Developing a dynamic partial equilibrium forest sector model for mainland Tanzania and assessing impacts of firewood and charcoal production and consumption on forest sustainability. In manus.

MUHTASARI

Sekta ya Misitu ina mchango mkubwa na inachangia kwa kiasi kikubwa moja kwa moja au kupitia njia mbadala katika kukuza Uchumi nchini Tanzania. Takribani asilimia 54 ya ardhi ya Tanzania Bara imekaliwa na uoto wa aina mbalimbali za misitu hususani misitu ya jamii ya miombo, vichaka vidogovidogo, mikoko pamoja na misitu minene ya kitropiki. Misitu inasaidia moja kwa moja au kwa njia mbadala sekta nyingine ikiwa ni pamoja na sekta za kilimo na utalii kupitia upatikanaji wa makazi ya wanyama, rasilimali maji na vyanzo vyake pamoja na kusawazisha kiwango cha maji ardhini na kuhifadhi Udongo. Inachangia kwa kiwango kikubwa katika mzunguko wa gesi mbalimbali hewani, upatikanaji wa bidhaa za kujengea, kipato pamoja na fursa mbalimbali za ajira.

Mavuno ya jumla ya mazao ya misitu nchini Tanzania ni vigumu kuyakadiria kwa usahihi lakini kutokana na takwimu za shirika la chakula na kilimo ulimwenguni (FAO) inakadiriwa kwamba mavuno ya mazao ya misitu kwa mwaka 2014 ilikuwa ni takribani mita za ujazo (m^3) milioni 40 ambazo zaidi ya asilimia 93% zilitumika kwa ajili ya kuni au kuzalisha mkaa. Nchini Tanzania zaidi ya asilimia 90 ya wakazi hutumia nishati kuni (kuni na mkaa) kama nishati kuu ya kupikia. Sehemu kubwa ya nishati kuni hizi huzalishwa katika misitu ya miombo ambayo kitakwimu inachukua takribani nusu ya eneo lote la misitu la Tanzania Bara. Uhitaji wa mazao ya misitu nchini Tanzania unaongezeka kwa kasi kutokana na kuongezeka kwa idadi ya watu, kukua kwa uchumi pamoja na ukuaji wa haraka wa miji. Kwa sasa idadi ya watu inakua kwa kiwango cha asilimia 2.7 kwa mwaka, uchumi wa nchi unakuwa kwa wastani wa asilimia 6.9 kwa mwaka wakati ukuaji wa maeneo ya mijini ni wastani wa asilimia 5 kwa mwaka. Ukuaji wa namna hii unamaanisha ongezeko kubwa la uhitaji wa ardhi yenye misitu pamoja na mazao yatokanayo na misitu.

Mkaa na kuni ni bidhaa muhimu sana kutoka kwenye misitu nchini Tanzania na ndiyo nishati kuu kwa ajili ya kupikia ambapo mkaa hutumika zaidi maeneo ya mijini. Uzalishaji na utumiaji wa kuni na mkaa unachangia kwa kiwango kikubwa katika kuwezesha maisha ya binadamu lakini matumizi haya yanaweza kusababisha madhara makubwa ya kimazingira. Nchini Tanzania, uhakika wa takwimu za sasa za matumizi ya nishati kuni ni mdogo sana, na pia utengenezaji wa mfumo husishi wa uhitaji na upatikanaji nishati kuni. Lengo la utafiti huu ni kuboresha uelewa wa kawaida kwa watu juu ya uzalishaji na matumizi ya sasa na ya baadaye ya mkaa na kuni na madhara yake katika usimamizi endelevu wa misitu pamoja na uzalishaji wa hewa ukaa. Zaidi hasa, tasnifu hii imejikita kwenye kujibu maswali ya kiutafiti yafuatayo:

Q1. Je, ni kwa kiwango gani ardhi imeharibiwa na uwezekano wa kuhuisha ardhi hiyo?

Q2. Je, ni taarifa gani muhimu ambazo tafiti za awali zinatupatia kuhusu uzalishaji na utumiaji wa mkaa na kuni nchini Tanzania?

Q3. Je ni nini athari za bei, kipato, ukubwa wa kaya na eneo la kijiografia kwenye matumizi ya mkaa katika maeneo ya mijini ya miji ya Dodoma, Morogoro and Mtwara?

Q4. Ni kwa kiwango gani inawezekana:

(i) kutengeneza modeli ya ulinganifu isiyokamilifu ya sekta ya misitu Tanzania bara ambayo mara zote na kwa usawa itaunganisha takwimu za aina ya miti mbalimbali, ukuaji wa misitu na ongezeko lake kutoka kwenye vishamba vya sampuli vipatavyo 32,000 vilivyopimwa kupitia mfumo wa Taifa wa takwimu za misitu Nchini Tanzania yaani NAFORMA pamoja na takwimu za kijamii na kiuchumi kuhusiana na uzalishaji na matumizi ya mkaa na kuni kwa sasa na hapo baadaye?; na

(ii) kutumia modeli hiyo ili kuchambua jinsi gani nadharia mbalimbali kuhusu ukuaji wa idadi ya watu, kiwango cha ukuaji wa miji na ukuaji wa uchumi vinaweza kuathiri matumizi ya baadaye ya mkaa na kuni, matumizi ya rasilimali ya misitu, uendelevu wa misitu na uzalishaji wa hewa ukaa Tanzania Bara?.

Katika tasnifu hii maswali haya yote yanajibiwa kwa mfumo wa maandiko manne, ambapo kila andiko linajibu swali lake. Nguvu kubwa ilielekezwa kwenye kutengeneza modeli ya ulinganifu inayoelezewa kwenye swali la nne - Q4, na mambo mengine yahusianayo na nadharia za matumizi ya ardhi au uchambuzi wa sera yanaelezewa kwa kifupi. Ufuatao hapa chini ni muhtsari kwa ufupi wa kila andiko pamoja na sura ya 4 na ya 5 ya tasnifu hii.

Andiko la kwanza (I) linalenga katika (i) kutathmini uwezekano wa uhuishaji wa ardhi katika mikoa mbalimbali ya Tanzania kwa kuzingatia takwimu mpya kwenye mfumo wa Taifa wa takwimu za misitu Tanzania (NAFORMA), na (ii) kutathmini uzoefu mahususi na matokeo ya kiuchumi yaliyopatikana katika tafiti za awali katika uhuishaji ardhi nchini. Imeonekana kwamba takriban asilimia 49 (sawa na hekta milioni 43.3) ya ardhi yote nchini Tanzania imeathiriwa kwa kiwango cha chini cha mmomonyoko (43%, sawa na hekta milioni 37.7), mmomonyoko wa wastani (5%, sawa na hekta 4.4) au mmomonyoko mkubwa (1.3%, sawa na hekta 1.2). Takwimu hizi ni kubwa na zina maanisha fursa kubwa za uhuishaji ardhi. Hivi sasa uharibifu wa ardhi ni wa kiwango cha juu, na baadhi ya maeneo yaliyoharibiwa yanaweza kupandwa miti tena, na hivyo kuongeza upatikanaji endelevu wa bidhaa za misitu na chakula na kudumisha faida za kimazingira, ikiwa ni pamoja na kuongezeka kwa mzunguko wa hewa ukaa kwa ajili ya kupunguza kasi ya mabadiliko ya tabia nchi. Ni tafiti chache sana za kiuchumi zimepatikana zinazoelezea faida na gharama za uhuishaji ardhi nchni Tanzania, hivyo tafiti mpya zinahitajika ili kutambua na kuweka vipaumbele baina ya shughuli mbalimbali za uhuishaji ardhi.

Katika *Andiko la pili (II)*, imewasilishwa tathmini ya tafiti mbalimbali za awali za uzalishaji na matumizi ya mkaa nchini Tanzania, na fursa mpya za kitafiti zinazovutia zimeweza kutambuliwa. Tafiti nyingi za kuvutia na za thamani zimefanyika, na inaonekana wazi jinsi ambavyo uzalishaji na utumiaji wa mkaa ulivyo na umuhimu katika mitazamo ya kijamii, kimazingira na kiuchumi. Hata hivyo, tafiti nyingi zilizopitiwa hazifafanui kwa uwazi mabunio na vipimo halisi vya nadharia za kitabia zilizotumika na zinazoweza kutumika kutengeneza mabunio ya kweli na yanayopimika. Imeonekana kwamba utafiti zaidi unahitajika kutafuta visababishi vya mahitaji ya mkaa kama vile mabadiliko ya bei, kipato na sera, na ili kupata takwimu hizi tafiti za kaya za kitaifa zinapendekezwa. Pia, tafiti zaidi zinahitajika kufanyika juu ya uotaji wa miti (muda na kiasi) katika misitu ya jamii ya miombo; jinsi gani aina mbalimbali za umiliki wa ardhi zinaathiri usimamizi wa misitu ya miombo; uwezekano na upendeleo wa uanzishaji mashamba ya miti kwa ajili ya kuzalisha mkaa nchini Tanzania; athari za jumla na za kipekee za sera; athari za hewa ukaa kutokana na uzalishaji na matumizi ya mkaa; utengenezaji wa modeli za kibailojia na kiuchumi zinazoweza kufanya uchambuzi unaofaa na kuweza kuelezea mabadiliko ya kijamii na kisera yawezekanayo kwa hali ya sasa.

Katika *Andiko la tatu (III)*, yamewasilishwa matokeo kutoka kwenye utafiti uliohusisha dodoso kwa kaya 360 katika miji mitatu ya Dodoma, Morogoro na Mtwara nchini Tanzania kuhusu madhara ya kipato cha kaya, bei ya mkaa na ukubwa wa kaya kwenye matumizi ya mkaa katika kaya husika. Uchambuzi wa kiuchumi ulifanyika kwenye sampuli nzima na katika makundi matatu ya kipato ili kutathmini ni kwa jinsi gani matumizi ya mkaa yanatofautiana kulingana na kipato cha kaya, bei ya mkaa, bei ya vyanzo vingine vya nishati ya kupikia, ukubwa wa kaya na jiografia ya eneo. Kwa sampuli nzima, kitakwimu inaonyesha kwamba kipato cha kaya, bei ya mkaa na ukubwa wa kaya vina umuhimu sana kwenye matumizi ya mkaa vikiwa na mnyumbuko wa 0.03, -0.13 na -0.62 kwa mfuatano huohuo. Katika kundi la kaya zenye kipato cha chini, mnyumbuko wa uhitaji na matumizi ya mkaa kwa mwaka ulikuwa muhimu kwenye bei ya mkaa na ukubwa wa kaya zikiwa na mnyumbuko wa -0.44 na -0.59 kwa mfuatano huohuo; katika kundi la kaya zenye kipato cha kati ni ukubwa wa kaya peke yake ndiyo ulikuwa na umuhimu kwa mnyumbuko wa -0.81 na katika kundi la kaya zenye kipato kikubwa kipato cha kaya kilikuwa muhimu kikiwa na mnyumbuko wa 0.17 pamoja na ukubwa wa kaya kwa mnyumbuko wa -0.44. Matokeo haya yanatokana na sampuli ndogo hivyo ni lazima yatazamwe kama mataokeo ya kiuchunguzi ya awali yenye thamani kwa ajili ya tafiti na dodoso kubwa zaidi hapo baadaye.

Andiko la IV lilikuwa na lengo kuu na la msingi la kutengeneza modeli ya ulinganifu isiyokamilifu ya sekta ya misitu Tanzania ambayo itaunganisha, kulinganisha na kubainisha upatikanaji wa mazao ya mbao na kuni na ulinganifu wa takwimu kutoka kitengo cha ukusanyaji takwimu za misitu za Taifa nchini Tanzania (National Forestry Inventory - NFI) yaani NAFORMA na mahitaji ya bidhaa zitokanazo na misitu na kutumia modeli hiyo kutahmini athari na madhara ya kimazingira katika usimamizi endelevu wa misitu yatokanayo na uzalishaji na matumizi ya kuni, mkaa na miti ya kujengea katika maeneo ya Tanzania bara. Modeli iliyotengenezwa (TanzFor) iko kwenye kundi la modeli linganifu isiyokamilifu na inalinganisha mahitaji na upatikanaji wa kuni, mkaa na miti ya kujengea pamoja na mazao mengine kwenye tasnia ya misitu katika mfumo thabiti wa kiuchumi. Utafiti huu ni wa kwanza kwa matumizi ya aina hii ya modeli linganifu isiyokamilifu barani Afrika kwa kutumia takwimu za kiundani kabisa za Taifa kutoka NFI kama NAFORMA pamoja na modeli nyingine mpya zilizotengenezwa za ukuaji wa misitu zinazoonyesha upatikanaji wa mazao ya misitu. Matokeo ya kitafiti ya modeli hii yanaonyesha athari hasi kwenye ongezeko la ukuaji wa misitu kwa sababu ya ongezeko la matumizi ya kuni na mkaa nchini Tanzania, linalosababishwa na viashiria mbalimbali vya kijamii na kiuchumi hususani ongezeko kubwa la idadi ya watu, viwango vya juu vya ukuaji wa miji, na ufanisi mdogo wa matumizi katika uzalishaji na utumiaji wa mkaa na uhuru wa kuingia na kuvuna kwenye ardhi yenye misitu.

Sura ya 4 ya tasnifu hii inatoa mtazamo wa jumla wa maelezo ya matokeo ya utafiti yaliyopatikana kwenye maandiko yote manne I-IV, na kujikita zaidi kwenye mambo yenye uwalakini, mwingiliano baina ya maandiko yote manne ya tasnifu hii, uhusiano kwenye nadharia za matumizi ya ardhi, umuhimu wa modeli ya sekta ya misitu kwa Tanzania, madhara ya kisera pamoja na tafiti za baadaye. Mada zifuatazo zimetajwa kuwa ni baadhi ya mada zenye kuvutia Zaidi kwa tafiti za hapo baadaye: Matumizi zaidi ya takwimu za misitu za Taifa kutoka NAFORMA katika kuchambua matumizi ya kuni na mkaa; kutoa takwimu sahihi zaidi juu ya matumizi ya sasa na ya baadaye ya mkaa na kuni; kuchambua athari za upatikanaji wa mazao mbao na kuni kutokana na mifumo tofauti ya umilikaji ardhi na utekelezaji wa sera mbalimbali; kuiboresha modeli ya sekta ya misitu ya Tanzania yaani TanzFor na sekta ya misitu kwa ujumla ikihusisha ubora wa takwimu zinazotakiwa kuingizwa pamoja na kuhusisha kwenye uboreshaji huo njia mbalimbali za umilikaji ardhi; kuitumia modeli ya TanzFor katika kukaridia uzalishwaji wa hewa ukaa na athari za mabadiliko ya tabia nchi kwenye sector ya misitu na pia kuitumia modeli hii ya TanzFor katika kukadiria na kutathimini athari za utekelezaji wa sera mbalimbali. Inasisitizwa, hata hivyo, kwamba kama zilivyo modeli nyingine, modeli ya TanzFor nayo ina mapungufu na ni urahisisho wa hali halisi ya maisha, na kwamba matokeo ya modeli zote ikiwemo TanzFor lazima yatafsiriwe kwa kuzingatia mambo hayo.

Katika Sura ya 5 imehitimishwa kwamba maswali manne ya kiutafiti Q1-Q4 yaliyowasilishwa hapo juu yamefanyiwa kazi na majibu mapya ya kiutafiti kupatikana na kuonyesha wazi kwamba matumizi ya sasa ya mazao ya misitu Nchini Tanzania si endelevu. Tanzania inakumbana na matumizi na ongezeko kubwa la uzalishaji na utumiaji mkaa haswa maeneo ya mijini ambako mkaa ndiyo nishati kuu ya kupikia. Matokeo ya kitafiti katika tasnifu hii yanaonyesha kwamba changamoto za uzalishaji na utumiaji wa kuni na mkaa yataendelea kuwa makubwa Nchini Tanzania kwa muda mrefu ujao ikiwa hatua stahiki hazitachukuliwa kuhakikisha kwamba nishati mbadala za kupikia badala ya mkaa na kuni zinapatikana kiurahisi na kwa bei nafuu zaidi kuliko ilivyo hivi sasa, na kuhakikisha kwamba uzalishaji wa mkaa unakuwa wenye ufanisi na tija zaidi.

SUMMARY

The forest sector plays a significant roles both directly and indirectly in Tanzania. In total 54% of the land area of mainland Tanzania is covered by different types of forests, the main ones being the miombo woodlands, woodland mosaics, mangrove and the tropical or rain forests with closed canopy. Forestry supports directly or indirectly other sectors including agriculture and tourism through provision of habitats for wildlife, water resources and catchments as well as maintaining hydrological balance and soil protection. It plays significant roles in biodiversity protection and recycling atmospheric gases, and provides construction materials, income and employment opportunities.

Tanzania's wood harvest volume is difficult to estimate, but according to FAO official statistics the country's total annual harvest of wood in 2014 was about 40 mill m^3 of which more than 93% was used for firewood or charcoal production. In Tanzania, more than 90% of the population use fuelwood (i.e. charcoal and firewood) as main source of energy. Most of this fuelwood is supplied from the miombo woodlands which covers about half of the forest area in mainland Tanzania. The country's demand of forest products is strongly increasing due to substantial economic and population growth and increased urbanization. Currently the population growth is 2.7% p.a., the economic growth is 6.9% p.a. while the urban population growth is about 5% p.a. Such growth rates imply increasing pressure on forest lands and forestry.

Charcoal and firewood are key products from the forest in Tanzania and are the country's main fuels for cooking, with charcoal mainly used in urban areas. Production and consumption of charcoal and firewood play a significant role in enhancing the livelihoods of people, but may also lead to adverse environmental impacts. In Tanzania, large uncertainties exist about the present quantities of fuelwood consumed, as well as about the future integrated development of fuelwood demand and supply. The main objectives of this study are to improve the knowledge base regarding the present and future production and consumption of charcoal and firewood in Tanzania and their impacts on forest sustainability. More specifically, the thesis addresses the following research questions:

- **Q1.** What is the extent of land degradation and land rehabilitation potential in Tanzania?
- **Q2.** Which information do previous studies provide about charcoal and firewood production and consumption in Tanzania?

Q3. What are the effects of price, income and household size on charcoal consumption in the three Tanzanian urban areas Dodoma, Morogoro and Mtwara?

Q4. To what extent is it possible to:

(i) develop a dynamic forest sector partial equilibrium model for mainland Tanzania which consistently links forestry data regarding tree species, forest growth and growing stock from about 32,000 single plots in Tanzania's national forest inventory NAFORMA, with socio-economic data regarding the country's present and future consumption and production of charcoal and firewood; and

(ii) apply this model for analyzing how assumptions regarding population growth, urbanization rate and economic growth would influence the future consumption and production of firewood, charcoal and poles, forest resource use, and forest sustainability?

In this thesis those questions are addressed in four papers, one for each question. Most efforts have been made in developing the quantitative model described in Q4, and issues related to theories of land-use or policy analyses are only briefly discussed. Below follows a summary of the papers and chapters 4 and 5 of the synopsis.

Paper I aims at (i) assessing the potential for land rehabilitation in various regions of Tanzania based on new data from NAFORMA, and (ii) reviewing main experiences and economic results gained in previous land rehabilitation studies in the country. It is found that about 49% (43.3 mill ha) of the total land area in mainland Tanzania is under either light (43%, 37.7 mill ha), moderate (5%, 4.4. mill ha) or heavy (1.3%, 1.2 mill ha) erosion. These figures are substantial and imply large opportunities for land rehabilitation. The present land degradation is high, and parts of the degraded areas could be reforested, thus giving increased sustainable supply of forest and food products and maintaining environmental benefits, including increased carbon sequestration for global climate change mitigation. Very few economic studies are found on the benefits and costs of land rehabilitation in Tanzania, and new studies are highly needed in order to identify and prioritize among the potential rehabilitation activities.

In *Paper II*, a review is presented of studies of charcoal production and consumption in Tanzania, and promising new research tasks are identified. Many interesting and valuable studies have been done, and it is clearly seen how important charcoal consumption and production are both in a social, ecological and economic perspectives. However, the results of the studies diverge a lot and most of the reviewed studies lack clear hypotheses and specifications of behavior theories to be used for developing realistic and testable hypotheses. It is found that more research is needed on factors effecting charcoal demand – like changes in prices, income and policies, and for that, using national household surveys is recommended. More research is also needed about tree regeneration (time and volumes) in miombo woodlands; how various forms of land ownerships influence miombo woodlands management; the possibilities and preferability in Tanzania of establishing forest plantations for producing charcoal; total and distributional impacts of policies related to production or consumption of fuelwood; climate gas emission impacts of charcoal production and consumption; development of bio-economic models which make possible consistent analyses of *ex ante* defined possible changes from the present socio-economic and policy situation.

In *Paper III,* results are presented from a survey of 360 households in the three Tanzanian cities Dodoma, Morogoro and Mtwara about the impacts of income, charcoal prices and household size on the household per capita charcoal consumption. For the total sample, statistically significant elasticities for charcoal per capita consumption were found to be 0.03, -0.13 and -0.62 for respectively per capita income, charcoal price and household size. In the low income group, statistically significant elasticities for annual charcoal per capita demand were found to be -0.44 and -0.59 for respectively charcoal price and household size; in the middle income group only household size was found to be statistically significant with estimated elasticity -0.81; and in the high income group elasticities of 0.17 for per capita income and -0.44 for household size were found statistically significant. These results are based on small samples and should be viewed as exploratory results of value primarily as information for larger surveys.

Paper IV has as primary objectives to develop a forest sector model which integrates wood supply from detailed forest data from Tanzania's NFI (National Forest Inventory) NAFORMA with demand for wood products, and apply this model to evaluate sustainability impacts of the future production and consumption of firewood, charcoal and poles in mainland Tanzania. The developed model (TanzFor) is classified as an intertemporally optimized spatial equilibrium model, and links in an economic consistent framework supply and demand for fuelwood, poles and charcoal as well as forest industry products. The study is the first one applying this kind of model in Africa with data from a detailed NFI as NAFORMA and newly developed forest growth functions as basis for the wood supply. The model results show alarming negative impacts on forest growing stocks by the steadily increasing consumption of firewood and charcoal in Tanzania, mainly caused by high population growth, high urbanization rates, low utilization efficiencies in both charcoal production and consumption, and rather free access to forest land.

Chapter 4 of the synopsis gives a more overall, perspectively oriented discussion of the results obtained in Papers I-IV, focusing on uncertainty, linkages between the four thesis papers, connections to land use theories, relevance of forest sector modeling in Tanzania, policy implications and future research. The following topics are mentioned as being among the most interesting ones for future research: Further use of the NAFORMA data in fuelwood analyses; provide more accurate data on the present and future consumption of charcoal and firewood; analyze wood supply impacts of various kinds of property right regimes and policy means; improving forest sector modelling in Tanzania both regarding data input quality and incorporation of land property/ownership specifications; applying the model in estimating GHG emission and impacts of climate change in the forest sector; using the model in estimating impacts of policy means. It is emphasized, however, that like all models *TanzFor* has weaknesses and is a simplification of real life conditions, and that all TanzFor model results should be interpreted with that in mind.

In Chapter 5 it is concluded that the above mentioned four research questions Q_1-Q_4 have been addressed and new results obtained which clearly show that the current consumption of wood in Tanzania is not sustainable. Tanzania is experiencing high and increasing production and consumption of charcoal particularly in urban areas where charcoal is the main type of energy for cooking. The results in this thesis indicate that challenges of fuelwood production and consumption will remain large in Tanzania for quite some time if no measures are taken to make cooking energy substitutes to charcoal more reliable and affordable than at present, and the charcoal production more efficient.

SYNOPSIS

1 INTRODUCTION

1.1 Background

The United Republic of Tanzania constitutes an area of 947,303 square kilometers and is the 13th largest country in Africa and the 31st largest in the world. This PhD study deals only with Tanzania mainland, which covers a land area (excluding lakes) of 86.1 million ha (URT, 2015). Regional differences are large in Tanzania both regarding vegetation types, forest growth potential, population growth, economic growth, urbanization as well as demand for different forest products. Figure1.1 shows the location and regions of mainland Tanzania.

According to the National Forestry Resources Monitoring and Assessment (NAFORMA) conducted by the Government of Tanzania from 2010 to 2014, Tanzania mainland has a forest area of 48.1 million ha, which constitutes about 55% of the total land area of mainland Tanzania, with a land use distribution as presented in Figure 1.2 (Tomppo *et al*. 2010; Vesa *et al*., 2010; Malimbwi and Zahabu, 2014). About 44.7 million ha (i.e. 93%) of the forest area is covered by woodlands which is important for charcoal production (Malimbwi and Zahabu 2014). The population in Tanzania mainland was in 2012 43.6 million people, implying a forest density of 1.1 ha per capita (URT, 2015).

Figure 1.1: Map of Tanzania and its regions

While all the national parks are owned by the state, forests are either owned or managed by the central government (forest reserves and catchment forests), local government, villages or individuals under their private lands. Other forests are located in general lands where all persons in the community have free access. Figure 1.2 shows main land ownerships and land use types in Tanzania.

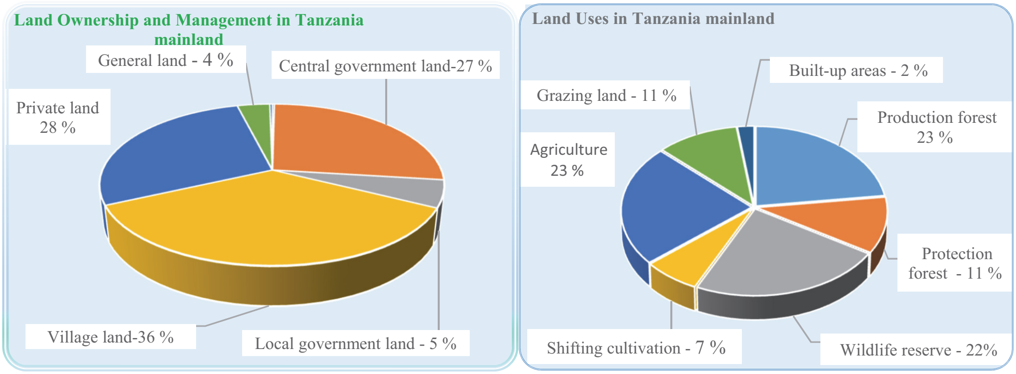

Figure 1.2: Land ownership and Land use distribution in Tanzania mainland (*Source*: URT, 2015)

In the following the term "forest sector" will be used rather often. It can be defined in several ways, but in this thesis the following definition is used: The term "forest sector" means a sector which comprises (i) the forests and the goods and services they provide, and (ii) the harvests of wood (including transport) and the productions based on the harvested volumes.

As such the forest sector plays a significant role in the entire economy of Tanzania, embracing a wide range of goods and services like providing firewood, charcoal, construction materials and carbon sequestration, as well as influencing biodiversity, wildlife habitat, water quality and landscapes. For local rural inhabitants, the provision of firewood, medicinal plants, meat through hunting wild animals, fodder for livestock, tannins, honey, beeswax, fibers and gums are perhaps the most direct benefits. The contribution of the forest sector (i.e. forest harvest and forest industries) to Tanzania's gross domestic product (GDP) is uncertain, but based on Abaza (2002) an estimate of about 3.5% of GDP around year 2000 seems realistic.

Large uncertainties exist about the quantities of wood harvests in Tanzania. FAO (2018) gives the following official annual harvested volumes for Tanzania including Zanzibar for 2014 (all figures rounded off to the nearest thousand):

Firewood coniferous	32,000	m^3
Firewood non-coniferous	23,900,000	m^3
Sawlogs and veneer logs coniferous	674,000	m^3
Sawlogs and veneer logs non-coniferous	111,000	m^3
Pulpwood coniferous	172,000	m^3
Pulpwood non-coniferous	37,000	m^3
Other industrial roundwood	1,616,000	m^3
Charcoal made of wood	1,816,000	tonnes

The industrial wood harvests sum up to 2.7 mill m^3. Assuming 7.5 m^3 wood input per ton of charcoal produced (Monela *et al*., 2007, Malimbwi *et al*., 2007), the wood harvested for charcoal and firewood adds up to 37.5 million m^3, thus constituting more than 93% of the estimated total harvest. The demand of forest products in Tanzania is growing rapidly, driven by substantial increases in key factors of the economy. The total population is growing at an average rate of 2.7% p.a., the economy as a whole is growing by about 6.9% p.a., and the urban population growth is around 5.0% p.a. (CIA, 2014). These high growth rates are likely to continue, implying increased demand for forest based services and products, hence creating even stronger pressure on land and forests.

1.2 Previous studies

Many studies exist regarding forests, forestry and the forest industries in Tanzania, and some are already quoted in the previous section. Also, in Paper II a rather detailed literature review of charcoal and firewood production and consumption is presented. In the following, I have therefore concentrated on literature which supplements the above mentioned ones and has relevance to consumption and production of firewood or charcoal.

According to Mwampamba (2007) and Lusambo (2016) more than 90% of the population in Tanzania use fuelwood (charcoal and firewood) as main source of energy, and estimated per capita annual consumption is about 1m^3 of wood (Schaafsma *et al*., 2012; Treue *et al*., 2014). Most of the fuelwood are supplied from the miombo woodlands. The forest sector supports directly or indirectly other sectors including agriculture and tourism through provision of water resources and catchments as well as maintaining hydrological balance and soil protection. Protection of the forests and other ecological habitats in Tanzania is vital because it is among the twelfth richest countries in terms of biodiversity in the world, having Africa's largest number of mammals, second largest number of plants (10,000 species), third largest number of birds (1,035 species), fourth largest number of amphibians (123 species) and fourth largest number of reptiles with about 245 species (Myers *et al*., 2000; Abaza, 2002; Burgess *et al*., 2002; Burgess *et al*., 2007; Pettorelli *et al*., 2010).

Several studies (like Malimbwi and Zahabu, 2014; Nyamoga *et al*., 2016), finds that the area of degraded land is increasing, and put land rehabilitation forward as a promising path for repairing damaged ecosystems and secure ecosystem functions, in order to enhance land productivity and provide essential goods and environmental services, including increased carbon sequestration for global climate change mitigation. In recent years Tanzania has been one of the developing countries piloting REDD+ projects as an instrument to address climate change challenges for both local and international benefits. The political will for undertaking and implementing REDD+ activities to achieve sustainable forest management is in place (Burgess *et al*., 2010). Studies indicate that, during the 1990-2010 period, Tanzania was the country with the fifth or sixth highest annual net loss of forest area in the world having an average annual loss of more than 400,000 hectares equivalent to 1.04 - 1.13% of the total forest area (FAO, 2010). This massive deforestation makes the forest and its related sectors to be a net carbon source emitter in Tanzania (FAO, 2010) and causing a range of environmental service damages that are lost as wooded land deforested and degraded.

In most growing cities in the world, the formal settlement growth and industrialization tend to be associated with an increase in income, availability of modern and commercial fuels (Hiemstra-Van der Horst and Hovorka, 2008). The increase in the household incomes tend to encourage these households to switch from the seemingly dirty and inconvenient traditional energy sources to those considered sophisticated and desirable fuels in the urban settings (DeFries and Pandey, 2010, DeFries *et al*., 2010). The energy ladder theory explains the transformation of traditional mainly rural-based societies to urbanized commercial and industrial economies, as associated with the aggregate shifts to modern fuels in the long-run. As the income of the household increases, that household will shift to the consumption of the more modern energy sources, thus moving from biofuel (cow dung–firewood) to charcoal, biogas, gas and electricity.

Several studies shows that charcoal production and consumption contribute significantly to the livelihoods of people and the charcoal production is high and increasing in the miombo woodlands (FAO, 2017; Luoga *et al*., 2000a,b; Malimbwi *et al*., 2007). The increasing number of charcoal producers in the miombo woodlands may be attributed to the free access and low capital required for starting charcoal production (Monela *et al*., 2007, 2001,1993). Most miombo woodlands are regarded as common pool resources freely available for everyone (Agrawal, 2003; Adams *et al*., 2003; Ostrom, 1990, 2008; Ostrom *et al*., 1994; Schlager and Ostrom, 1992) and therefore profit-maximizing charcoal producers will continue producing charcoal as long as profit is maximized. Although most of the biomass for charcoal production is highly concentrated in the naturally regenerating miombo woodlands, there is an increasing trend of investments in plantations for charcoal production in tropical regions including Tanzania (Chidumayo and Gumbo, 2013). The decrease of the size of woodland area causes increased marginal value of each remaining tree (Hofstad, 1997; Luoga *et al*., 2000a). Despite the importance of charcoal as an income generating activity for the households, the inefficient traditional earth kilns are the main production technologies used with very low efficiency (11-30%) leading to higher wood biomass use (Luoga *et al*., 2000a,b). With this low kiln efficiencies, about 70-80% of the wood biomass are lost during the production process implying increased deforestation.

Charcoal production and trading have been perceived negatively and linked to deforestation and forest degradation because of the historical unsustainable production technologies employed (Jones, 2002; Kissinger *et al*., 2012; Cerutti *et al*., 2015), and in some countries new regulations are now put in place for supporting sustainable charcoal production (Delahunty-Pike, 2012). The unsustainable charcoal production in turn affect the livelihoods of people because of reduced land and ecosystem productivity. According to FAO (2010), Tanzania is among the top ten global charcoal producers producing about 3% of the world's total charcoal produced. The charcoal sector therefore is important in contributing to economic development and poverty alleviation in Tanzania, and it is important to address holistically the entire charcoal value chain from the producers to the consumers (Neufeldt *et al*., 2015; Luvanda, 2016). Severals studies show results implying that charcoal will dominate the energy sector for many years in most countries in Sub-Saharan Africa (FAO, 2017; Hosier *et al*., 1990; Hosier and Kipondya, 1993; Hosier *et al*., 1993; World Bank, 2009; Sander *et al*., 2013).

Deforestation and degradation of forested land account for about 10-20% of the global GHG emissions (Achard *et al*., 2004; Gullison *et al*., 2007; Parry *et al*., 2007; Van der Werf *et al*., 2009; Baccini *et al*., 2012; Harris *et al*., 2012), which is very high even compared to the transportation and energy sector (Brown, 2008). Deforestation and land degradation due to over-exploitation and agricultural expansion leave the poor communities more vulnerable to poverty due to lack of income alternatives and are at the same time causing multiple negative environmental effects (Appiah *et al*., 2009, Hartmana *et al*., 2014).

In most countries the forest sector is rather complicated, and in several industrialized countries it has during the last four decades been found useful to develop forest sector models for incorporating and analyzing main biophysical and economic interactions in the forest sector (Latta *et al*., 2013). Forest sector models are essential tools in providing consistent analysis of factors such as production, consumption, trade, and prices of roundwood and forestry industry products and how these factors respond to changes in external factors like economic growth, forest biodiversity, forest protection and management regulations, energy prices, trade regulations, transport systems and costs, exchange rates, forest growth and behavior of the consumers (Kallio *et al*., 2002). To my knowledge it has previously in Tanzania been only two studies where forest growth (as wood supply) and forest product consumption (as wood demand) have been analysed in an integrated way at national level. The first study applying a forest sector model for Tanzania was developed by Ngaga (1998), and was probably the first one applied in Africa. The main objective of the model was to analyse the interactions between the country's demand for forest industry products with the supply of wood from forest plantations. The model was a dynamic-recursive forest sector model, which integrated timber supply, the processing industries, product demand and the trade among the regions including the export and import to maximize the sum of consumer and producer surpluses. Charcoal and firewood as well as sawnwood production from indigenous forests were not included in the model. The second study is a simulation model for analyzing forest degradation impacts of charcoal consumption in Dar es Salaam and published in World Bank (2009). The model is a simple spreadsheet model made in Excel, with no dynamic forest growth or partial equilibrium aspects included, and is primarily used to simulate how household demand and various policy means impact the use of forest resources. None of the two studies had possibilities of using a National Forestry Inventory (NFI) as detailed as NAFORMA.

In Tanzania, also some other types of bio-economic models than those applied in Ngaga (1998) and World Bank (2009) have been developed. These models include multi-objective regional forest planning (MOP) by Allen (1986), linear programming models and General Processing Models (GPM) by Kowero and Dykstra (1986, 1988). These models are valid for rather small areas and cannot provide a consistent analysis of the whole Tanzanian forest sector (Allen 1986, Kowero and Dykstra 1986, Kowero and Dykstra 1988).

Today, we have more information than before about the importance of charcoal and firewood. In addition we have through the national forest inventory NAFORMA (URT, 2015) much better data regarding forest growth and growing stock, making it possible to include rather detailed wood supply data at regional level (for a more detailed description of the inventory see Chapter 2.1).

1.3 Study objectives and research questions

Summing up the studies referred to in the preceding sections it became clear that many factors regarding the Tanzania forest sector are burdened with high uncertainty. In particular, three main interlinked topics were found to be both important and possible to include in the frame of this PhD study: (a) Improved information on the potential for land rehabilitation, (b) improved information about the production and consumption of charcoal and firewood, and (c) developing and applying a forest sector model for mainland Tanzania focusing on demand and supply of firewood and charcoal. The choice of these three topics were further strengthened because NAFORMA data were made available that would provide considerable better forest data than previously possible.

Based on this, the main objective of this study is to improve the knowledge base regarding the present and future production and consumption of firewood, charcoal and poles in Tanzania and their impacts on forest sustainability. More specifically, the thesis addresses the following research questions:

Q1: What is the extent of land degradation and its rehabilitation potentials in Tanzania?

Q2: Which information do previous studies provide about charcoal and firewood production and consumption in Tanzania?

Q3: What are the effects of price, income and household size on household charcoal consumption in the three Tanzanian urban areas Dodoma, Morogoro and Mtwara?

Q4: To what extent is it possible to:

(i) develop a dynamic forest sector partial equilibrium model for mainland Tanzania which consistently links forestry data regarding tree species, forest growth and growing stock from the single plots in Tanzania's national forest inventory NAFORMA, with socio-economic data regarding the country's present and future production and consumption of firewood, charcoal and poles; and

(ii) apply this model for analyzing how assumptions regarding population growth, urbanization rate and economic growth would influence the future production and consumption of firewood, charcoal and poles, forest resource use, and forest sustainability's in mainland Tanzania?

Because of time limitations, most efforts have been made in developing the quantitative model mentioned in Q4, and issues related to theories of land-use or policy analyses are only briefly discussed in chapter 4.

The questions Q1-Q4 correspond respectively to the four scientific papers attached at the end of this thesis. Compared to the existing literature these papers contribute in my opinion with new research knowledge or insights in several ways: *Paper I*, addressing Q1, is the first published study using data from Tanzania's newly established national forest inventory NAFORMA to estimate the country's areas of degraded land and their distribution on regions and degradation severity. As such the paper should provide more accurate information on Tanzania's land degradation than previous estimates. The paper also gives a brief overview of experiences gained in previous land rehabilitation projects in Tanzania, and finds that very few economic studies exist on the benefits and costs of such projects. *Paper II*, addressing Q2, gives an overview of results of previous studies of charcoal and firewood production and consumption in Tanzania. The paper provides new information as it structures the surveyed studies on which behaviuor theories and statistical methods they have applied, the area/scope covered and empirical results gained. *Paper III,* addressing Q3*,* provides new empirical results of urban charcoal consumption, and is one of rather few econometric studies done in Tanzania on this topic. *Paper IV*, addressing Q4, documents the first intertemporal forest sector model made for Tanzania (and perhaps for Africa) directly linked to a national forest inventory, and provides new results regarding sustainability impacts of future charcoal and firewood consumptions in the country.

Each of the research questions Q1-Q4 is addressed separately in the respective papers I-IV, but all papers deal with consumption or production of charcoal and firewood in one way or another. Paper I, II and III can be seen as providing important inputs to the forest sector modelling in Paper IV.

The remaining part of the synopsis is structured as follows: In chapter 2, methods and data are described more in detail. In chapter 3, the main results of each of the four papers are presented. In chapter 4, the results are discussed with a perspective view across the papers, and suggestions for promising future research tasks are presented. In chapter 5, main conclusions are drawn. In addition, the synopsis have two appendices: The first giving a mathematical description of TanzFor and the second presenting research permits and persons/institutions visited in Tanzania for data collection. Finally, as last parts of the thesis, the four research papers are presented in full length.

2 METHODOLOGY

In this chapter the data and methods applied in each of the respective papers I-IV are described.

2.1 Methodology Paper I

Paper I is based on new data from NAFORMA and previous literature on socio-economic studies of rehabilitating degraded lands in Tanzania.

NAFORMA provides data on forest standing volume and growth for 32,773 sample plots in Tanzania, distributed on tree species classes, vegetation types and regions. The NAFORMA set of data is probably the best forestry information available in any country in Africa, and is detailed described in Vesa *et al*. (2010a,b) and Malimbwi and Zahabu (2014). The forestry data is based on original data from the 32,660 sample plots of NAFORMA which are clustered in 3,419 statistically representative grid structures as described in URT (2010) and URT (2015). One fourth of the sample plots are permanent. The plot data are classified according to 28 vegetation types, 9 land use categories and 6 ownership classes.

In Paper 1 the data were structured and analyzed according to regions, vegetation types and degree of degraded land. NAFORMA uses a stratified systematic cluster sampling design (Vesa *et al*., 2010a,b). The distance between plots within a cluster is 250 m, and the sampling plots were located in different positions depending on the distance between clusters and the number of plots within a cluster. Depending on the accessibility of the area, about 6 to 10 plots are established in each cluster (Vesa *et al*., 2010a,b).

The reported data in NAFORMA about erosion were used as indicator for land areas potentially available for rehabilitation. NAFORMA operates here with four categories (NAFORMA 2015):

- *No* erosion - i.e. “No evidence of erosion”
- *Light* erosion- i.e. “Slight erosion where only surface erosion has taken place”
- *Moderate* erosion – i.e. “Erosion where mild gullies and rills are formed on the top surface of the soil”
- *Heavy* erosion – i.e. “Areas which have deep gullies, ravines, land slips etc.”

2.2 Methodology Paper II

Paper II is based on a desk survey of articles in peer-reviewed journals and a few unpublished governmental and consultancy reports with sufficiently high scientific quality. Whenever necessary when using the unpublished reports, the report producers and owners were contacted for clarifications. Google Scholar was applied as search engine for finding publications to be included in the study. The main selection criteria were:

(i) Having charcoal in Tanzania as main element and covering at least one of the above stated sub-objectives;
(ii) Published in peer-reviewed research journals or in governmental or consultancy reports which are publically available and of sufficiently high scientific quality; and
(iii) Published after 1990.

Regarding criterion (i) we made exceptions regarding studies on GHG emission and included few studies which cover countries in East Africa or Sub-Saharan Africa, but are relevant also for Tanzania.

The research resulted in sixteen articles published in peer-reviewed research journals and five governmental or consultancy reports. For each of the selected studies focus was on presenting methodology and main results. Regarding methodology, it was emphasized to include behaviour theories assumed, geographical area covered, sample size, main variables studied and statistical method applied. Including behaviour theory in this overview was done because any statistical study of consumption or production to be realistic ought to be based – implicitly or explicitly – on factors which reflect as well as possible the behaviour of the producers or consumers studied.

2.3 Methodology Paper III

Theory and hypotheses

Houshold economic theory was chosen as behavior model underlying the development of the questionnaire and statistical analysis, i.e. it was assumed that a household allocates its income on expenditures (food, housing, energy, travels, school fees etc.) to get as high utility (or welfare) as possible given the constraints set by the household income and the prices of goods and services. Formally, it was assumed that a household maximizes yearly welfare of purchased goods and services, conditional on household income I and prices for various energy sources (p_1 for charcoal, p_2 for gas, p_3 for electricity) and other commodities and services (p_o). This gives the following short-term demand function for charcoal in household i (see e.g. Varian, 1996, 2014):

$$d_i = d_i\,(p_1, p_2, p_3, p_o, I)$$

According to economic theory the hypothesis is that d_i decreases with increasing p_1 and increases with increasing p_2 and p_3, all other factors assumed equal. The impact of increased I is less certain, but here we used the energy ladder theory, which posits that households will shift to more advanced and clean energy types as income increases (Hiemstra-Van der Horst and Hovorka, 2008), giving as hypothesis that charcoal consumption decreases with increasing income, all other factors equal.

Data collection and statistical analysis

The collection of data for Paper 3 was done as a special charcoal consumption survey conducted during the period June-September 2015 in each of the three urban areas Dodoma, Morogoro and Mtwara. The three urban areas were selected purposively because they have some main different socio-economic activities, are surrounded by some different vegetation types and are located in different distances from Dar es Salaam, the main charcoal market and business center in Tanzania.

A total of 120 households from each area were interviewed. The households were selected to represent respondents from low-income, middle-income and high-income categories. Among other questions in the survey, the respondents were asked about the price of charcoal per given unit (bag, sack or tin), amount of charcoal consumed per month, week or day, total annual or monthly income and the size of the household. The questionnaire used in the survey is shown in Paper III.

The selection of respondents were done in two stages. First, in each of the three urban areas, the population was divided into different income levels by classifying the city wards and streets into three groups reflecting respectively the low, middle and high income households. The identification and classification of the wards on different social status was done in close collaboration with local government officials in order to capture the actual income differences in the cities. The households in the selected wards and hamlets were then assigned numbers and later drawn randomly in each street using the population registry in the local leaders' offices, in order to get sufficient number of respondents in each income class. Based on the income reported in the interviews the households were categorized into the following three income classes: (i) Low income – consisting of households with income less than Tshs 3,000,000 per annum, (ii) Medium income – comprising households with an income between Tshs 3,000,000 and 10,000,000 per annum and (iii) High income – containing households with income greater than Tshs 10,000,000 per annum. As very few of the survey respondents were using gas or electricity for cooking prices of gas and electricity were exluded in the statistical analysis.

To avoid heteroscedasticity in the econometric estimation we used per capita charcoal consumption as the dependent variable and income per household member as independent variable. We also included number of household members as independent variable to reflect possible economies of scale in cooking. Prices of electricity and gas were excluded because very few of the respondents reported use of these energy sources in cooking. The final econometric equation thus became:

$$\log C = a + b_1 \log P + b_2 \log I + b_3 \log H + \varepsilon$$

where:

C is per capita consumption of charcoal (kg per capita per year)
P is price of charcoal (Tshs per kg)
I is annual per capita income (Tshs per year per person)
H is number of persons per household
a, b_1, b_2, b_3, are coefficients to be estimated and ε is the error term.

The original data set were first checked for outliers by performing influence measures tests, and altogether 27 of the observations were removed because of missing values and abnormalities. The statistical analyses were thus done using 333 households in the whole sample, of which 71 (21%) were high-income households, 142 (43%) were middle-income households and 120 (36%) were low-income households.

The data were analyzed using R program, version 3.2.5 - 2016-04-14 (Crawley, 2013). To check for heteroscedasticity Breusch Pagan Test (lmtest and NCV test) in R were used (Breusch and Pagan, 1979).

2.4 Methodology Paper IV

In Paper IV the forest sector model TanzFor is described, and NAFORMA and functions for forest growth, mortality and biomass are used to provide the wood supply inputs to TanzFor.

NAFORMA is already described in chapter 2.1. In Paper IV it was assumed that fuelwood, poles and charcoal could be taken from all vegetation types except from the land types protected forests and forest reserves, wildlife reserves, and mangrove forests. Regarding plantations it was allowed for poles and fuelwood extractions in *Eucalyptus* and *Acacia Mearnsii* plantations, and in *Acacia Mearnsii* plantations also for charcoal production. In each of the regions the NAFORMA sample plot data were used to find standing volumes for various species and vegetation types in the base year 2014. To simulate the future development of each of these plots, the growth, mortality, and recruitment functions in Mugasha *et al*. (2017) were used. Stem and branch volumes were estimated using equations from Mauya *et al*. (2014), and biomass in above-and-below ground components was estimated using the functions in Mugasha *et al*. (2013). The growth projections begin in 2014 and were conducted up to a total of twenty 5- years' periods thus allowing evaluation of harvest possibilities during a 100-year time frame.

The core center of this study was the development of the TanzFor model, which in the terminology of Latta *et al*. (2013) can be characterized as an intertemporally optimized spatial partial equilibrium model of the forest sector of mainland Tanzanian. TanzFor links consistently economic driven demand for firewood, poles and charcoal, as well as other forest products, with wood supply determined by detailed data from NAFORMA sample plots and newly developed forest growth functions. The harvest in each region depends upon the costs of production and transport and the regional willingness to pay for wood. TanzFor includes 25 domestic regions to capture the regional differences in terms of vegetation types, forest growth potential, population growth, economic growth, urbanization as well as demand for forest products and interregional trade. In addition one foreign region is included in the model to ensure that imports and exports are incorporated to balance the market and product movements. The Tanzanian net foreign trade volumes of firewood, charcoal, poles, sawnwood and other forest industry products are rather small, and in this study they are assumed to remain in the future as they were in 2014.

Formally, TanzFor can be characterized as a dynamic, spatial equilibrium model where the market clearing prices and quantities are found by maximizing the discounted sum of regional net social surpluses less transportation costs between regions. One difference from the Samuelson (1952) approach lies in the treatment of timber supply which is not driven by supply curves, but rather through harvest scheduling combining the features of a Johnson and Scheurman (1976) model I and II formulation. Any part of a NAFORMA plot can either experience a partial harvest thus reducing forest stock, affecting ingrowth, and altering the growth rate, or a regeneration harvest in which case the plot returns to age zero. Upon harvest the logs are allocated to a forest product incurring a product-specific manufacturing cost prior to being transported to a region to meet its demand. Demand for each product in each region is defined by a constant elasticity demand function set at the current price and quantity and shifted over time based on exogenously determined levels of population and technological growth. This non-linear specification is solved by linear programming using piece-wise integration over a scenario-specific time period (up to 100 years). Time steps are current 5-years and a real discount rate of 6% p.a. was used in the analyses.

A set of model constraints control the land and harvest allocation as well as ensuring balance in supply and demand. A mathematical description of the model laying out the piecewise integration of the objective function and nine constraints defining acreage allocation, harvesting, and market-clearing equilibrium is found in Appendix 1. A more detailed description is given in Paper IV's Appendix 1.

3 RESULTS

3.1 Paper I: Potentials for rehabilitating degraded land in Tanzania

The specific objectives of Paper I were to assess the degraded land areas potentially available for rehabilitation in various regions in Tanzania, and give a review of main experiences and economic results gained in previous land rehabilitation studies in the country.

New data specified for this study from Tanzania's National Forestry Resource Monitoring and Assessment (NAFORMA) were applied for determining the size of degraded lands in the various regions of the country. For each region and vegetation type, the erosion was classified into light, moderate and heavy categories as defined in chapter 2.1. Moderate erosion in % of forest land area was found in Arusha (11%), Iringa (10%), Dodoma (9%), Kilimanjaro (9%), Kagera (9%), Morogoro (8%), Njombe (8%), Tanga (7%) and Ruvuma (7%). Generally, about 49% (43.3 mill ha) of the total land area in Mainland Tanzania was found to be under either light (43%, 37.7 mill ha), moderate (5%, 4.4. mill ha) or heavy (1.3%, 1.2 mill ha) erosion.

Regarding vegetation types, the largest erosion area were found in the humid montane forested land, where 61% of the area or about 530,000 ha had erosion of some kind. Also the plantation area and the lowlands experienced large erosion, respectively 38% (about 220 000 ha) and 37% (about 660,000 ha) of the total plantation area. In the Woodland category, scattered cropland had the highest relative erosion area (76% or about 1.9 mill ha), while light and moderate erosion occurred in the Humid montane forest (59%), Woodlands (51%), Grasslands (49%), cultivated agroforestry system (47%) and in other land uses (41%).

In the paper several reasons are mentioned as factors causing this erosion. The national population census of 2012 show Kagera and Arusha to be among the regions with the highest annual population growth rates of 3.2% and 2.7% respectively, indicating the influence of the population pressure on the erosion. Also, different topographies, vegetation types and weather conditions in different regions in Tanzania subjects them to various degrees of land degradation. Forest activities like inappropriate logging and farming practices (over cultivation and overgrazing) tend to cause land degradation. In some areas, the migration of pastoralists with large number of cattle from one region to the other have caused significant deforestation (Charnley, 1997a,b). These movements have been a major source of land use conflicts between pastoralists and farmers in Morogoro, Tanga and other regions in Tanzania. Poor land property regimes are also an important reason for these conflicts leading to improper land use management. The miombo woodland are mainly managed under free access basis hence subjecting them to severe harvesting for charcoal and clearing for agricultural activities (Hofstad, 1997; Luoga *et al*., 2000; Kajembe *et al*., 2005; Mwampamba, 2007; Mbwambo *et al*., 2012).

Paper I shows large potentials for land rehabilitation in the country. Delaying interventions and leaving these eroded areas unattended increase the economic losses in terms of the opportunity costs of lost crop yields, pasture quality, forest products and other woodland benefits (Misana *et al*., 2003). In spite of this, Paper I reports that none economic studies were found which have calculated the benefits and costs of land rehabilitation in Tanzania.

Paper I concludes that previously, only scant information was available on the extent and amount of land degradation in Tanzania, but now the NAFORMA data clearly document that the country is experiencing serious land degradation problems. These problems are exacerbated by significant changes in population, economic growth and demand of forest products. The land use changes need proper attention to ensure sustainable supply of forest and food products and maintaining environmental benefits and services, including increased carbon sequestration. Agroforestry and tree planting programs are potential techniques for rehabilitating degraded land in Tanzania because of the expected multiple economic and environmental benefits to the community and the country. Updated and enlarged economic studies are highly needed in order to identify the most promising land rehabilitation activities. Impacts of land-property regimes are important to consider. As the permanent plots in NAFORMA will be re-estimated with regular intervals, more accurate data of the erosion areas will be available, including data about the erosion changes over time.

3.2 Paper II: A Review of Studies Related to Charcoal Production, Consumption and Greenhouse Gases Emission in Tanzania

Paper II confirms that biomass mainly from trees is the major source of energy in both urban and rural areas in Tanzania and that in most urban centers, charcoal is the main source of cooking energy, while firewood dominates in rural areas. The production of charcoal contribute significantly to the income of people along the value chain, and several of the reviewed studies report that this production is increasing in the miombo woodlands (Luoga *et al*., 2000a; Malimbwi *et al*., 2007). Very few studies have been done on the whole charcoal value chain despite the increasing number of charcoal producers. Several studies argue that two main factors behind the increasing charcoal production are free access to the miombo woodland and the low capital required for starting charcoal production (Monela *et al*., 2007, 2001 and 1993). The price of charcoal in urban areas has increased every year due to increasing demand.

Studies included in Paper II show that in urban areas the preferences for charcoal are much higher than for other cooking energies, due to its high calorific value per unit weight (Felix and Gheewala, 2011) and cost competitiveness as well as conveniences in transporting, storing use and non-susceptibility to infections by fungi. Varying figures were reported on the quantity of charcoal consumed and the wood biomass required for producing charcoal in Tanzania. For example Malimbwi *et al*. (2007) reports that about 3.6 million m^3 of wood was needed to produce 28,759 bags (each weighing 56 Kg) consumed daily in Dar es Salaam, whereas other studies report that the city's annual consumption of charcoal in 2009 was 1 million tons and that this quantity required about 30 million m^3 of wood (Peter and Sander, 2009; Sander *et al*., 2013).

Many of the studies included in Paper II highlights that the demand for charcoal in urban areas will be increasing in the coming decades until when affordable substitutes are available to the market (Hosier and Kipondya, 1993; Hosier *et al*., 1993; Mwampamba, 2007; Lusambo, 2016; Nyamoga *et al*., 2016). Several of the studies emphasize that the growing demand for charcoal increases the opportunities for income generation for both rural and urban population through production and trade hence contributing to poverty alleviation (Van Beukering *et al.,* 2007, Zulu and Richardson, 2013), but could also easily lead to increased deforestation, unsustainable production and environmental degradation.

The review's main conclusions are as follows: Many of the reviewed studies lack clearly hypotheses and specifications of behavior theories to be used for developing realistic and testable hypotheses. More research is needed on factors effecting charcoal demand – like changes in prices, income and policies, and for that, using national household surveys is recommended. More research is needed also about tree regeneration (time and volumes) in miombo woodlands; how various forms of land ownerships/property regimes influence miombo woodlands management; the possibilities and preferability in Tanzania of establishing forest plantations for producing charcoal; total and distributional impacts of policies; GHG impacts of charcoal production and consumption; the development of bio-economic models which make possible consistent analyses of *ex ante* defined interesting changes from the present economic and policy situation.

3.3 Paper III: Econometric analysis of urban households charcoal consumption in Tanzania

In Paper III, for the whole sample, all three variables were found statistically significant, with elasticities being -0.13 for price and 0.034 for per-capita income (Table 3.1). The negative coefficient of -0.621 for the household size shows a rather strong economies of scale effect.

Dividing the respondents into three income level groups, per-capita income is significant only for the high-income group, with an elasticity of 0.17. Price is significant only in the low-income group, with elasticity of -0.44. Household size is significant in all three subsamples; with elasticities of -0.59, -0.81 and -0.44 in respectively the low, medium and high income group. The adjusted R^2 varies from 0.22 in the high-income group to 0.41 in the low-income group.

Table 3.1: Regression results of full sample and three income level samples

	Full sample (n=333)		Low income (n=120)		Middle income (n=142)		High income (n=71)	
	Coefficients	SE	Coefficients	SE	Coefficients	SE	Coefficients	SE
Intercept	6.138***	0.472	7.689***	1.075	8.490***	1.891	2.628	1.583
Per capita income	0.034*	0.020	0.061	0.066	-0.159	0.108	0.167*	0.094
Price of charcoal	-0.130**	0.063	-0.442***	0.102	-0.024	0.108	0.057	0.135
Household Size	-0.621***	0.055	-0.590***	0.082	-0.814***	0.081	-0.440**	0.160
Adjusted R^2	0.3162		0.414		0.3279		0.2195	
F-value	52.17		29.12		23.92		7.564	

'***' significant at level α = 0.01, '**' significant at level α = at 0.05 '*' significant at level α = 0.10

Also other statistical models were tried, like having total household consumption as dependent variable and charcoal price, total household income and household size as independent variables, and to exclude household size, as well as not using logit transformation. These specifications all gave lower R^2 and lower F-values, or positive coefficient for the charcoal price. Including region as explanatory variable, the price coefficient turned insignificant, probably due to the large differences in price levels between the three regions. These models were therefore rejected.

The charcoal price demand elasticity estimated for the low income group is significantly higher (in absolute term) than for the whole sample. This indicates that the poor families are living on a very strict household budget and are highly sensitive to changes in charcoal prices compared to the richer families. The result is in line with other Tanzanian studies e.g. (Hosier and Kipondya, 1993; Hosier *et al*., 1993; Zein-Elabdin, 1997; Sanga and Jannuzzi, 2005; Peter and

Sander, 2009) which report that the high initial costs required tend to limit the low-income households to invest in electric, gas and improved charcoal cooking stoves.

In our study, charcoal price is not statistically significant in the middle and high income households. For the richer households increased charcoal prices within the range observed in this study, might still result in charcoal being both cheaper and more reliable than shifting to electricity or kerosene cooking. Food tradition and taste considerations may also work for charcoal cooking in those groups.

For the entire sample the regression analysis resulted in a small, but positive per capita income elasticity of 0.03 statistically significant at 10% level. In the three stratified income samples, the per capita income variable was found statistically significant only in the high income group with elasticity 0.17. One should be very careful in drawing implications from these results, in particular those from separated income groups as the income variations within these groups are considerably smaller than for the whole sample. Nevertheless, it is noteworthy that the only statistical significant variables we found were positive, as it may indicate that the transition of going from charcoal to more modern cooking facilities like kerosene and electricity might take longer time than expected. Mwampamba (2007) and Hosier and Kipondya (1993) also found that income did not have significant effects on charcoal consumption in the households they investigated.

The study results are based on small samples and should therefore be interpreted and used with caution. Larger studies of charcoal consumption in Tanzanian households than this study are strongly needed, and should preferably be based on larger samples, include more regions and higher number of respondents who have moved from charcoal use to modern cooking energy carriers, and include accurate data on the consumption and costs of these carriers. To get enough number of respondents, it is suggested to coordinate such studies with existing governmental household surveys done regularly in Tanzania.

3.4 Paper IV: Developing a dynamic partial equilibrium forest sector model for mainland Tanzania and assessing impacts of firewood and charcoal production and consumption on forest sustainability

The main results in Paper IV show the impacts of three alternative scenarios regarding the development of future fuelwood use in Tanzania, labelled respectively Low, Base and High scenario. This classification relates to the following assumed technological improvements over time in charcoal production (i.e. kiln efficiency estimated as m^3 wood biomass used per ton of charcoal produced) and charcoal consumption (i.e. household stove efficiency measured as kg charcoal used per capita):

- In Base ("Medium") alternative: 0.5% p.a.
- In High charcoal consumption alternative: 0.25% p.a.
- In Low charcoal consumption alternative: 1.0 % p.a.

When the model was run using the Base scenario demand for 100 years (2014 - 2114), it was unable to maintain harvest levels past 2059 when assuming that harvests took place only on land were harvest is legally allowed. Based on this it was decided to apply the model in three different sets of analyses giving three sets of results. The first set focuses on sustainability and how long-term demand can be met when (i) using only the forest areas allowed today for harvesting, and (ii) also using today's forest reserves – i.e. forest areas not allowed to be cut. This set of results shows the pressure which the Base scenario would bring on utilizing restricted forest land.

The second set of analysis isolates the demand component of the model for charcoal, fuelwood and poles in the three technological scenarios Base, Low and High defined above, and assuming no wood supply constraints – i.e. only the wood demand assumptions based on growth in urban and rural population in each region and the technological improvements defined above are taken into account.

The third set of analysis again uses the full model yet concentrates on the period 2014 - 2059 and shows the impacts of each of the three scenarios Base, Low and High defined above. In addition to the harvest and inventory levels, the regional differences in price effects are explored. Below we report the results of the first and third set of analyses.

Figure 3.1 shows the TanzFor model results for the Base scenario of 100-years of harvesting with and without maintaining the 15.6 million hectares of protected areas and reserves. It is indicated in the left panel that the harvestable inventory rises to year 2044 when the protected areas and reserves are maintained and later falls dropping by over one half by the end of the 100-year time horizon. On the other hands, the right panel tells some more of the story as the harvest rises through 2059 and then hovers at approximately 150 million cubic meters per year before eventually falling precipitously in 2079 through the end of the modeling time horizon as the merchantable trees on harvestable lands are exhausted.

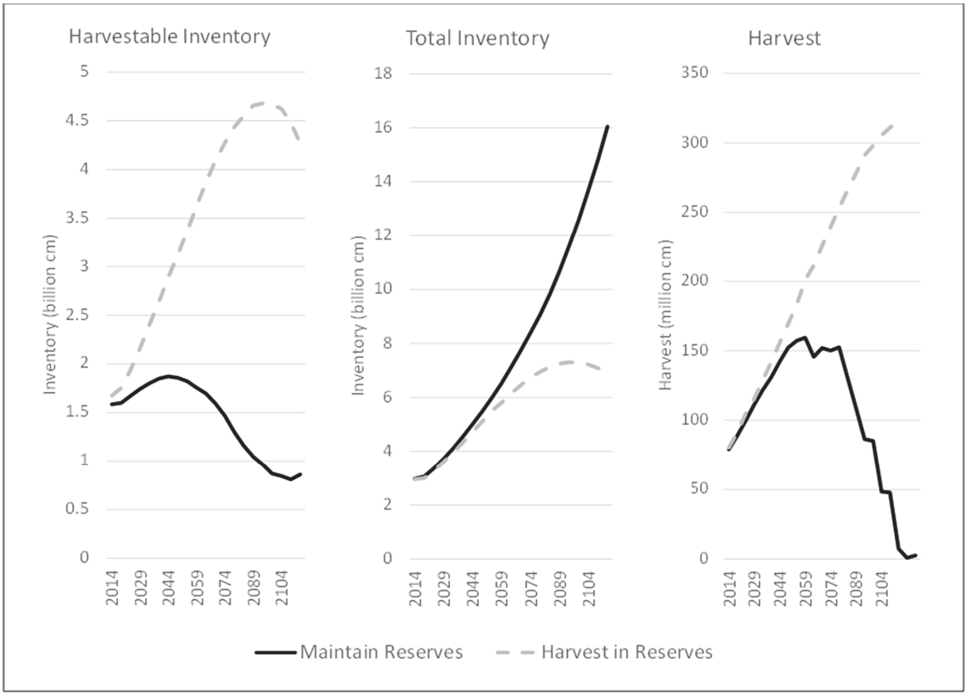

Figure 3.1: *Results of nationwide harvestable inventory, total inventory, and harvest levels with and without maintaining protected areas and reserves in mainland Tanzania.*

The dashed lines in Figure 3.1 indicate what the situation would be if the pressure of not meeting demand over the next century leads to a breakdown of the protected area and reserves, and harvesting takes place across all forests of mainland Tanzania. In the left panel we see that the stocks on harvestable lands triple before beginning to fall in 2094. The middle panel shows that the inventory decline at the end of the century which is consistent with that of the harvestable lands, and indicate that while utilizing all forest land of Tanzania avoids the midcentury collapse of harvest, adding in protected forests only adds another half century before all forests are in decline.

The third set of results concentrate on the period 2014 - 2059 and analyse the impacts of each of the three scenarios Base, Low and High defined above, assuming that harvest only can take place in forest areas presently allowed for harvests. The results are shown in Figures 3.2 and 3.3.

Figure 3.2 highlights sustainability criteria in the form of (a) total inventory in both protected area and harvestable areas, (b) nationwide harvestable inventory, and (c) harvest level of wood for firewood, charcoal and poles. The harvest levels of the Low, Base, and High scenarios culminate in 2059 harvest levels of 148, 192, and 219 million m^3 respectively. These harvest increases of 1.8, 2.4, and 2.8 times the 2014 levels lead to a 2059 harvestable inventory level that is 92%, 68%, and 46% of initial levels for the Low, Base and High scenarios respectively. In each case the total inventory rises as volume accumulates in forest reserves, nearly doubling.

Figure 3.2: *Development in mainland Tanzania of (a) forest growing stock in areas where harvest is allowed, (b) forest growing stock in both protected area and harvestable areas, and (c) harvest level of wood for fuelwood, charcoal and poles during 2014-2054 for the Low, Base and High scenarios assuming no harvest in forest reserves and protected land*

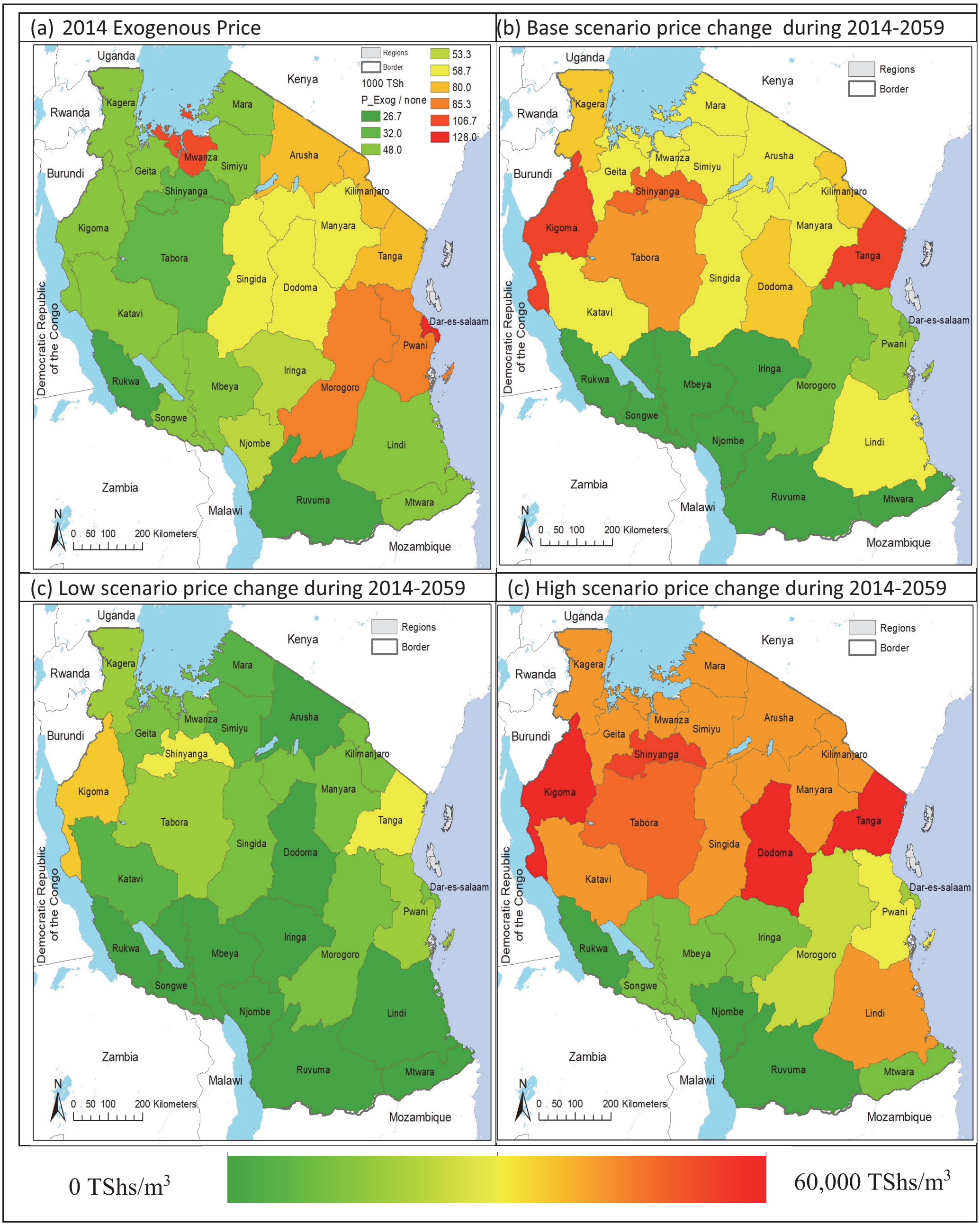

Figure 3.3: *(a) Regional prices of charcoal in base year 2014, and (b) the corresponding price changes from 2014 to 2059 in the scenarios Base, Low (c) and High (d) (in '1000' Tshs per m³ fuelwood used for producing charcoal)*

The four panels of Figure 3.3 highlight the exogenous starting price in 2014 for charcoal in each Tanzanian region along with the estimated change in the charcoal prices over the 2014 - 2059 time period.

Figure 3.3a shows the geographic distribution of charcoal prices which are higher in the east due to the dominance of the Dar es Salaam. The other area of higher prices is Mwanza region which is the second largest charcoal market in the country. Figure 3.3b demonstrates that the increases in price are manifested not in the actual regions of highest demand (Dar es Salaam and Mwanza) but rather in the adjacent regions which serve as supply zones to the larger markets. With the exception of Lindi, the north part of the country experiences price increases whereas the south sees little real price increase. The Low scenario price change map of Figure 3.3c avoids the degree of price increases of the Base scenario, with the largest price increases contained in the Kigoma region where the 34,000 TShs/m^3 increase constitutes a 70% real price increase over its 48,000 TShs/m^3 price in 2014. The High scenario shown in Figure 3.3d leads to price increases as high as 60,000 TShs/m^3 in all regions except the southeastern regions.

Paper IV documents that an intertemporally optimized spatial partial equilibrium model of the Tanzanian forest sector (TanzFor) has been constructed and applied for analyzing forest sustainability issues related to the future development of the country's consumption and production of firewood, charcoal and wooden poles. TanzFor links in an economic consistent framework supply and demand for fuelwood, poles, charcoal, sawnwood and other forest industry products.

The future increase in the production and consumption of fuelwood, poles and charcoal found in Paper IV is alarming. Even in the Low charcoal consumption scenario defined above, where rather strong technological improvements both regarding production and consumption of charcoal are assumed, one see decreasing growing stocks in the forest areas allowed for harvests.

4 DISCUSSIONS

The methods and results presented in chapters 2 and 3 are discussed rather detailed in the respective *Papers I-IV*. This chapter, therefore, aims at giving a more overall, perspectively oriented discussion of the results in those papers, concentrating on uncertainty, linkages between Papers I-IV, connections to land use theories, relevance of forest sector modelling in Tanzania, policy implications and future research.

4.1 Uncertainty

Although based on best available data, nearly all of the input data used and results obtained in this thesis are uncertain. *Paper I*, using NAFORMA data, is the paper with the lowest uncertainty as the results showing area distribution of degraded land and regions, are based on data from 32,660 inventory plots structured statistically as described in URT (2015). At present only the area size and distribution of the different degrees of erosion are presented, but when new rounds of NAFORMA are made, it will be possible to calculate with relatively high certainty also the rate of change over time of the erosion and its distribution on regions and various erosion degrees.

Paper II shows large variations in the existing estimates of the consumption of charcoal and firewood. In addition very few studies were found on GHG emissions in the production as well as consumption of charcoal in Tanzania.

Paper III aimed at finding more accurate estimates about the urban per capita consumption of charcoal and factors influencing it. Also here, large variations were found. The sampling method applied within each of the urban areas investigated could have influenced the results, as could also the interpretation of the respondents' answers during the interviews.

Paper IV is based on many uncertain factors. The uncertainties described above for the Papers I, II and III are to a large degree carried over to the forest sector analyses done in Paper IV. In addition, the paper includes several other factors having considerable uncertainty, like the assumed population growth, economic growth, urbanization rate, forest growth, transport costs as well as the assumed agent behaviour. This is further discussed in section 4.3.

Illegal logging is one uncertainty factor common for all papers except Paper I. Very few published studies have quantified illegal tree cuttings and logging for charcoal production in

Tanzania. However, the TRAFFIC project reports (Milledge and Elibariki 2005, Milledge and Kaale 2005, Milledge et al. 2007) find that illegal timber harvests could be 30–70% of total harvest in the miombo woodlands. Such high shares may mislead both statistics, conclusions and policy recommendations.

4.2 Linkages between Papers I-IV

Ideally, as mentioned in chapter 1.3, one could view Paper I, II and III as providing vital inputs to the forest sector modelling in Paper IV. Paper II was important in getting an overview of previous studies showing estimates of per capita consumption of charcoal and firewood and factors affecting the consumption. Together with the consumption data from Paper III, this gave empirically based regional estimates of the consumption of charcoal in the starting year of the forest sector analysis in Paper IV. Paper II provided the model initial data also for firewood and poles.

The intention was that Paper III should provide empirically based estimates of price- and income elasticities for charcoal demand, which then could be directly applied in TanzFor. The price elasticity used in paper IV is based on the estimates in Paper III. Also, the choice of having zero income demand elasticity for charcoal in Paper IV was based on the results obtained in Paper III.

The information from NAFORMA obtained in Paper I regarding land degradation and potentials for land rehabilitation was not directly used in Paper IV. However, that information could be very useful for finding suitable rehabilitation areas and documenting bio-economic impacts of rehabilitation in later studies applying the TanzFor. Also, one might argue that documentation in Paper I of the magnitude of degraded land areas and lack of economic analyses in Tanzania about the costs and benefits of land rehabilitation, could create more interests in the studies done in Paper IV.

4.3 Connections to land use theories

Meyfroidt *et al*. (2018) and Lambin *et al*. (2011) gives a rather thorough overview of theories explaining the causes of land-use change and their systematic linkages across places, defining change in land use as *"the purpose and activities through which people interact with land and terrestrial ecosystem"*. As such, the studies provided in this thesis are linked, directly or indirectly, to changes in land use. Regarding Paper I, the linkage is indirectly, as only the actual present extent of land degradation is provided and reasons for the degradation are not taken up. In Paper II, one result is that rather few of the reviewed studies have specified any behavior theory underlying their analyses. Furthermore, the studies there of production costs and wood supply do not consider any stumpage values or silviculture investments, because it is indirectly assumed that the wood is taken from common land with free exploitation access or weak authority regulations. In Paper III, household economic utility maximization behavior is assumed for guiding the choice of dependent and independent regression variables in the econometric study, and the link to land-use is indirectly primarily through the price of charcoal, per capita income and household size.

Paper IV is based on neo-classical economic theory, assuming competitive markets and that forest harvest takes place if the paying ability for wood in the market is higher than the harvest costs and it is not profitable to delay the harvest to a later period. A particular challenge enter here, however, as most of the wood harvest in Tanzania is coming from forest land which can be classified as a Common Pool Resource (CPR) – i.e. land with no or unclear ownership and where everyone can harvest, either because it is common land or because property regulations are weak.

In fact, in Tanzania, the livelihood of the majority of people especially the peasant and pastoral communities in rural areas, depends on farming on village lands and exploitation of natural resources from CPR lands. The resource use from these general lands has created severe conflicts between different land users as well as illegal productions. According to Ostrom (2009), any resource which is highly valuable and large is subjected to collapse if it is under open-access systems and when the resource users are diverse, do not communicate, and fail to develop rules and norms for managing such a resource.

One main challenge regarding analyzing fuelwood harvest on CPR land is that impacts of non-market goods and services like e.g. biodiversity, water availability and erosion are not considered when harvests are decided. There is a substantial literature base focusing on resource utilization on CPR lands (e.g. Agrawal, 2003; Adams *et al*., 2003; Ostrom, 1990, 2008; Ostrom *et al*., 1994) and it is beyond the scope of this thesis to go into detailed discussions of these matters. However, it should be noted that the structure of the TanzFor model allows for a variety of methods by which non-market values can be considered - for example as extra costs of harvest, or as obliged regeneration costs depending on harvest intensity, or as harvest constraints on certain vegetation or property types. Likewise, the model allows for introducing additional costs associated with enforcement and monitoring necessitated by policy changes designed to alter harvests or behaviour. By including relevant costs and benefits, TanzFor can be used to analyse the overall preferability of introducing new forest land policies.

However, models like TanzFor cannot solve CPR land problems, but they can contribute by showing the impacts of various policies and thus provide a better basis for wise decision making regarding land use and land use policies.

4.4 Relevance of forest sector modelling in Tanzania

The expected main advantage of developing the forest sector model TanzFor was rather clear. It should give an appropriate tool for providing bio-economic analyses which consistently combine (a) detailed forest supply data from NAFORMA, (b) forest growth data from recent forest yield research like Mugasha *et al*. (2013, 2017), and (c) socio-economic data which determine the demand for charcoal and firewood, like population growth, economic growth, urbanization rates, transport costs, and technology changes.

With such a tool it should be possible to analyse more realistically than before how changes in policies and any of the assumed model input factors may influence the Tanzanian forest sector, for example as shown in Paper IV.

This advantage comes with the challenges described above in sections 4.1- 4.3, and it is important to ask how relevant is it to apply an intertemporal dynamic forest sector model like TanzFor in a developing country like Tanzania. Handling uncertainties regarding model input data in forest sector models are discussed rather detailed in Kallio (2010), Chudy *et al*. (2016), Buongiorno and Johnston (2018) and Jaastad *et al*. (2018). One conclusion common for these studies is that ordinary sensitivity analyses and Monte Carlo simulations are the most realistic ways of dealing with uncertainty in forest sector models. TanzFor is a dynamic forest sector model, i.e. optimizing over the whole analyzing period, in contrast to the so called dynamic-recursive forest sector models which apply only static optimization for each period. Each simulation in TanzFor takes a long time, and providing many hundreds of runs as required in Monte Carlo simulations is not realistic with TanzFor at present available computer capacities. We are therefore left with sensitivity analyses as the best way of getting information on how uncertainties in TanzFor input data influence the model results.

The agent behavioral assumptions made in forest sector models are discussed in e.g. Latta *et al*. (2013) and Sjølie *et al*. (2011a,b). It is beyond the scope of this thesis to go into details here. However, it is questionable to assume for a developing country like Tanzania that agents have perfect information and that free competition prevails in the forest sector, as is the case in TanzFor. As such, the TanzFor results should be interpreted as optimal solutions under the two strong assumptions that the agents involved (i.e. charcoal and firewood producers and consumers, transport providers) have perfect foresight and that free competition prevails. This means that the TanzFor results are likely to give lower market prices and higher market quantities of charcoal and fuelwood than what would be the case in "real life". It seems reasonable to assume that information about present prices is well known, as e.g. the availability of mobile phones in Tanzania is good. The assumption of full knowledge about future prices and quantities is, however, unrealistic. To reduce this problem, Latta *et al*. (2013) propose to combine static and intertemporal optimization forest sector models into hybrid models which *"could move sequentially through time utilizing the intertemporal optimization model solution for harvest levels, manufacturing capacity additions, and silvicultural investment then use those outputs to guide the recursive dynamic model's short-run solution which would then, in turn, update the starting conditions for the intertemporal optimization solution in the next time period"*. In the case of Tanzania this would require to develop a recursive dynamic forest sector model for Tanzania and combine that with TanzFor. In principal that would not be difficult, because all model input data necessary for a recursive dynamic model would be available from TanzFor; however, in practice this was not possible within the limited time for this PhD study.

In TanzFor the opportunity cost of postponing the harvest is included through the assumed time-dependent optimization objectives, whereas in reality fuelwood harvests on CPR land is focused on present profit generation and may not consider the future development of the harvested forest area. Thus, if the majority of fuelwood harvests in Tanzania originate on land exhibiting strong CPR characteristics, the TanzFor modeled harvest results might be lower than what would happen in real life. With TanzFor, the assumed choice of interest rate will influence the strength of this impact – the higher the assumed interest rate is, the closer the model results will be to "pure" CPR behavior, all other factors equal. This behavior can also be approximated by lowering the harvest costs in the model.

As mentioned in section 4.3 there are some possibilities for including in TanzFor impacts of non-market goods and services like e.g. biodiversity, water availability and erosion.

Summing up, I would like to conclude here that even if intertemporal models like TanzFor and also recursive-dynamic models have several weak points as described above, better alternative quantitative methods for analysing main supply and demand interactions in the Tanzanian forest sector over time do not exist to my understanding. An important point is to interpret the results of the models with their weaknesses in mind.

4.5 Policy implications

Notwithstanding the challenges discussed in chapters 4.1- 4.4, one main policy implication of the results shown in this thesis is that the present use of firewood and charcoal in Tanzania is not sustainable, and thus that new policy means have to be introduced in order to get a more sustainable land-use.

Another rather robust finding with possible policy implicationsis is that there exist in Tanzania large areas of degraded land available for afforestation or reforestation – for fuelwood as well as for industrial wood production. The main challenge is to utilize these opportunities optimally.

As stated in chapter 1.3, because of time limitations it has been beyond the scope of this PhD study to include direct policy analysis like for example analyzing effectiveness or efficiencies of policy means. However, one strong advantage of forest sector models like TanzFor is that they are very suitable for analyzing impacts of policy means as differences over time between model results with and without the policy or set of policies analysed. Earlier studies have proposed numerous policy means for getting a more sustainable fuelwood sector in Tanzania. World Bank (2009) is one of the most comprehensive studies in that respect, proposing numerous policy means for improving forest management, charcoal carbonization efficiencies, domestic trade and wholeselling, and consumption efficiencies. Almost all of the quantitative policy means proposed in World Bank (2009) can be incorporated in TanzFor and evaluated with respect to their effectiveness and efficiency, as well as distributional impacts. This could be one important contribution of TanzFor in the future.

4.6 Future research

The study has revealed many interesting tasks for future research, the following ones being among the most urgent ones:

Further use of the NAFORMA data

In this study only NAFORMA's data on forest growing stock and area distribution on different vegetation types have been used. The collected soil data from the permanent sample plots have yet not been used, but could give interesting results regarding carbon sequestration in soil. The same is the situation regarding utilizing the social survey part of NAFORMA. There, many thousands households have been surveyed regarding their use of forest and firewood, and the collected data if properly analysed, could give valuable and statistically representative information about household fuelwood consumption in all regions of Tanzania.

When re-measurements of NAFORMA are completed, one would get possibilities of estimating also the change over time regarding forest growth, carbon sequestration in soil, land degradation, and fuelwood harvest and consumption. These data will be very useful for calibrating the present applied forest growth models, carbon sequestration rates and fuelwood consumption changes, and for improving the quality of TanzFor's input data.

Provision of more accurate data on the consumption of charcoal and firewood

Paper II reveals large variations in the estimates of present per capita consumption in Tanzania of both charcoal and firewood, as well as on factors deciding the consumption. More research is needed here, covering the whole country and being built on proper theories of household behavior. For this, utilizing the rather detailed data in the social survey part of NAFORMA could be interesting. Another way would be to get charcoal and firewood more explicitly included in the official national household surveys being conducted in Tanzania. A third way is to perform studies like in Paper III in other urban areas of Tanzania. Such surveys should in addition to sample stratifications on income, also try to stratify on households which within the last 2-3 years have changed their main type(s) of cooking energy. As such, one could get improved empirical information about which factors influence such changes, and thus provide a better basis for prognosis about the future fuelwood consumption development and for improved policy making.

Analyses of costs and benefits of land rehabilitation

Paper I showed that very few studies exist on the costs and benefits of land rehabilitation projects in Tanzania. More studies on this topic is required, covering factors like choice of tree species, promising use of agro-forestry techniques, and the importance of various incentives and land-ownerships. The dominance of charcoal among the different types of cooking energies in Tanzania seems to be a long term process. Setting aside land and promoting plantations for charcoal production using tree species with high calorific values like *Acacia Mearnsii* seem promising.

Improving the structure of TanzFor and forest sector modelling in Tanzania

Most of the above mentioned research tasks would contribute to improving forest sector modelling in Tanzania. In addition, existing forest plantations are already included in NAFORMA and TanzFor, but possibilities of investing in new forest plantations of various kinds are not included in the present version of TanzFor. This however, would be relatively easy to implement and should be incorporated in a revised model version. The same is the situation regarding soil carbon sequestration, which also rather easily can be included in TanzFor using existing NAFORMA data. NAFORMA includes all forests in mainland Tanzania described at plot level, and if appropriate biodiversity indicators were developed, one could use TanzFor to analyse how biodiversity would be impacted by for example varying harvest developments in indigenous forests or new investments in forest plantations. It would also be interesting to develop a recursive-dynamic forest sector model for Tanzania based on the data input in TanzFor, in order to check how important the assumptions of perfect foresight is for a country like Tanzania – cf. the citation in section 4.2 from Latta *et al.* (2013).

Applying TanzFor in policy analysis related to land-use and climate mitigation **issues**

If the above suggested improvements of TanzFor were made, the model would include the whole carbon cycle of Tanzania's forest sector, as well as other important sustainability factors like forest biodiversity, land erosion, and indoor air pollutions caused by the use of charcoal in urban areas. The current variability in rainfall and climate conditions in Tanzania makes it also of high interest to include climate change scenarios in the TanzFor model by cooperating with relevant climate model groups. The inclusion of climate change scenarios might provide more comprehensive land-use analysis and policies.

As already mentioned in section 4.3, forest sector models are particularly useful for analyzing impacts of policy proposals. Each policy or set of policies imply different costs and benefits over time, thus giving different results regarding policy effectiveness and efficiency as well as distributional impacts. Using TanzFor to estimate such impacts, the model could prove to be a very useful tool for policy makers in analyzing and searching for appropriate land-use policies, being it REDD+ policies or other related to sustainable land-use in Tanzania.

5 CONCLUDING REMARKS

The main objective of this PhD study has been to improve the knowledge base regarding quantitative information about the present and future production and consumption of charcoal, firewood and wooden poles in Tanzania and their impacts on forest sustainability, addressing the four research questions specified in section 1.3.

The methodology and main results are described and discussed in chapters 2, 3 and 4 of this synopsis. It is my opinion that all four questions have been addressed and new results regarding sustainable forest sector development in Tanzania provided.

In Paper I it is concluded that the present land degradation in Tanzania is high, and that a substantial parts of the degraded areas could be reforested, thus giving increased sustainable supply of forest and food products and maintaining environmental benefits, including increased carbon sequestration for global climate change mitigation. However, very few economic studies are found on the benefits and costs of land rehabilitation in Tanzania, and new studies are needed in order to identify and prioritize among the potential rehabilitation activities.

The review in Paper II of studies of charcoal production and consumption in Tanzania concludes that many interesting and valuable studies have been done, and that it is clearly seen how important charcoal consumption and production are both in a social, ecological and economic perspectives. However, the results of the reviewed studies diverge a lot and most of them lack clear hypotheses and specifications of behavior theories to be used for developing realistic and testable hypotheses. It is emphasized that more research is needed particularly on factors effecting charcoal demand – like changes in prices, income and policies, and for that, using national household surveys is recommended.

The econometric study in Paper III of per capita charcoal consumption of 360 households in the three Tanzanian cities Dodoma, Morogoro and Mtwara gave statistically significant elasticities for per capita income, charcoal price and household size. It is concluded that although these results are interesting, they are based on a small sample and should be viewed as exploratory results of value primarily as information for larger surveys. Future studies of this kind should be done, preferably in due contact with larger more general household surveys.

The forest sector model TanzFor is in Paper IV documented and applied to evaluate sustainability impacts of future consumption of fuelwood in Tanzania. TanzFor is classified as an intertemporally optimized spatial equilibrium model, and links in an economic consistent framework supply and demand for fuelwood, poles and charcoal as well as forest industry products. The wood supply in TanzFor is based on detailed forestry data from 32,773 sample plots in NAFORMA. It is concluded that the model results show alarming negative impacts on forest growing stocks by the steadily increasing consumption of firewood and charcoal in Tanzania, mainly caused by high population growth, high urbanization rates, low utilization efficiencies in both charcoal production and consumption, and rather free access to forest land.

In the more overall, perspectively oriented discussion in chapter 4, the following topics are taken up: uncertainty, linkages between the four thesis papers, connections to land use theories, relevance of forest sector modeling in Tanzania, policy implications and future research. Most of the wood harvest for fuelwood in Tanzania originates from CPR land. This situation related to common land utilization and weak property regimes creates challenges for any kind of forest sector modelling in Tanzania. Various approaches to meet at least some of these challenges are mentioned in chapter 4. However, even if TanzFor seems to be a promising tool for integrated forest land-use analyses in Tanzania, it is emphasized that TanzFor has several weaknesses and represents, as all models, a simplification of real life conditions. As such, all TanzFor model results should be interpreted with that in mind.

One main policy implication of the results shown in this thesis is that the present use of firewood and charcoal in Tanzania is not sustainable, and thus that new policy means have to be introduced in order to get a more sustainable land-use. Another rather robust finding with possible policy implications is that there exist in Tanzania large areas of degraded land available for afforestation or reforestation – for fuelwood as well as for industrial wood production. The main challenge is to utilize these opportunities optimally.

As stated in chapter 1.3, because of time limitations it has been beyond the scope of this PhD study to include direct policy analysis like for example analyses of effectiveness or efficiencies of policy means. However, as mentioned in chapter 4.3, one strong advantage of forest sector models like TanzFor is that they are very suitable for analyzing impacts of policy means as differences over time between model results with and without the policy or set of policies analysed. Compared to other forest land modelling in Africa, TanzFor has a strong advantage in being able of using the detailed forestry data in NAFORMA, coupled with relevant forest yield and mortality functions.

Tanzania is experiencing high and increasing production and consumption of charcoal particularly in urban areas where charcoal is the main type of energy for cooking. The results in this thesis indicate that fuelwood production and consumption will remain high in Tanzania for quite some time if no measures are taken to make cooking energy substitutes more reliable and affordable than at present, and the charcoal production and consumption more efficient.

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7 APPENDICES

Appendix 1: Mathematical description of TanzFor

This appendix gives a formal specification of TanzFor. The first part lists symbols used in the paper and has been organized into three groupings; sets, parameters, and variables. Sets, for which we have used lower case letters, are collections of sub-sets overs which the model is defined. Parameters, again designated by lower case letters, represent exogenous data which may or may not be defined over a group of sets. Finally, upper case letters indicate endogenous variables determined by the model which may or may not be defined over a group of sets. Then follows the specification of the objective function and constraints that comprise TanzFor.

1. Sets

- f is the set of forest silvicultural regimes which include a no harvest option along with a clear-felling or partial harvest option for each time period
- n is the set of 15,180 National Forestry Resources Monitoring and Assessment (NAFORMA) forest inventory plots
- p is the set of forest products either produced or consumed within the model
- r is the set of 25 Tanzanian regions
- s is the set of 100 equal steps over which the area under forest products demand is broken into
- y is the set of 20, 5-year time periods, y^{-1} would indicate the first time period *(2014-2019)*

2. Parameters

- a_n forest area in hectares parameter for NAFORMA plot n
- c_{py} parameter indicating the forest product non-wood costs of manufacturing product p in year y
- h_{rpys} parameter indicating the height of each rectangle associated with of the s equal steps that are used in the piece-wise integration of the area under the demand curve for forest product p in region r in time period y
- i parameter indicating the discount rate (%)
- m_{py} parameter indicating the exogenous foreign imports or forest product p in time period y
- $o_{p'p}$ parameter indicating forest product manufacturing coefficient indicating amount of forest product p required to produce one unit of product p'
- $t_{pr'r}$ parameter indicating the per unit cost of transporting product p from region r' to region r
- v_{nfy} parameter indicating clear-felling harvest yield on NAFORMA plot n enrolled in forest silvicultural regime f in time period y
- w_{rpys} parameter indicating the width of each rectangle associated with of the s equal steps that are used in the piece-wise integration of the area under the demand curve for forest product p in region r in time period y
- x_{py} parameter indicating the exogenous foreign exports or forest product p in time period y
- z_{nfy} parameter indicating partial harvest yield on NAFORMA plot n enrolled in forest silvicultural regime f in time period y

3. Variables

- A_{nfy} variable indicating area in hectares of NAFORMA plot *n* assigned to silvicultural regime *f* assigned a regeneration harvest in year *y*
- C_y variable indicating the sum of transportation and manufacturing costs in time period *y*
- D_{rpys} variable indicating the proportion of each of the *s* equal steps that the area under the demand curve in region *r* for forest product *p* in time period *y*
- H_{rpy} variable indicating the annual harvest in region *r* for forest product *p* in time period *y*
- I_{rpy} variable indicating the annual foreign imports to region *r* for forest product *p* in time period *y*
- M_{rpy} variable indicating manufacturing in region *r* of forest product *p* in time period *y*
- $R_{nfy'y}$ variable indicating area in hectares of NAFORMA plot *n* assigned to silvicultural regime *f* regenerated in year *y'* and assigned a regeneration harvest in year *y*
- S_{rpy} variable indicating the annual supply in region *r* for forest product *p* in time period *y*
- $T_{r'rpy}$ variable indicating the trade of forest product *p* inside Tanzania between region *r'* and region *r* in time period *y*
- W_{rpy} variable indicating the annual waste or unused production in region *r* for forest product *p* in time period *y*
- X_{rpy} variable indicating the annual foreign exports from region *r* for forest product *p* in time period *y*

4. Mathematical specification of TanzFor

The TanzFor model consists of an objective function that implements piecewise integration of the forest product demand curves allowing for solution as a linear programming problem and nine sets of constraints controlling area allocation, harvest calculation, supply and demand balancing, and cost accounting.

Objective function

The objective function (Equation A1) used in the linear program involves the maximization of the discounted sum of the net social surplus.

$$MAX \sum_{y}\left(\sum_{r}\sum_{p}\sum_{s}\left(D_{rpys} * w_{rpys} * h_{rpys}\right) - C_y\right) * (1+i)^{-(y-y^1)} \qquad \text{(A1)}$$

Constraints

$$\sum_{f}\sum_{y} A_{nfy} = a_n \quad \forall n \qquad \text{Allocation of all available area (A2)}$$

$$\sum_{y'} R_{nfyy'} = \sum_{f'}\sum_{y'} A_{nf'y'} + \sum_{f'}\sum_{y'} R_{nf'y'y} \quad \forall n, f, y \qquad \text{Allocation of all available area (A3)}$$

$$5 * H_{rpy} = \sum_{n}\sum_{f}\left(A_{nfy} * v_{nfy}\right) + \sum_{n}\sum_{f}\sum_{y':y'>y}\left(A_{nfy'} * z_{nfy}\right) + \sum_{n}\sum_{f}\sum_{y':y'<y}\left(R_{nfy'y} * v_{nfy}\right) \quad \forall r, p, y$$

Annual harvest calculation (A4)

$$H_{rpy} + M_{rpy} + \sum_{r'} T_{r'rpy} + \sum_{p'}\left(M_{rpy} * o_{p'p}\right) = S_{rpy} + \sum_{p'}\left(M_{rp'y} * o_{p'p}\right) + \sum_{r'} T_{rr'py} + X_{rpy} \quad \forall r, p, y$$

Supply balance (A5)

$$S_{rpy} = \sum_{s} D_{rpys} \quad \forall r, p, y$$

Demand balance (A6)

$$\sum_{r} X_{rpy} = x_{py} \quad \forall p, y$$

Foreign Export limitation (A7)

$$\sum_{r} M_{rpy} = m_{py} \quad \forall p, y$$

Foreign Import limitation (A8)

$$\sum_{r}\sum_{p}\left(M_{rpy} * c_{py}\right) + \sum_{r'}\sum_{r}\sum_{p}\left(T_{r'rpy} * t_{pr'r}\right) = C_{y} \quad \forall y$$

Industry costs (A9)

$$D_{rpys} \leq 1 \quad \forall r, p, y, s$$

Demand integral step limit (A10)

Appendix 2: Permits for doing research work in Tanzania and persons/institutions visited

2A: Permits from Different Authorities for Conducting Research in Tanzania

United Republic of Tanzania
MINISTRY OF NATURAL RESOURCES AND TOURISM
TANZANIA FOREST SERVICES (TFS) AGENCY

Address : "TFS" P.O.BOX 40832
Tel No : (+255) (022) 2864249 DAR ES SALAAM
Fax No : (+255) (022) 2864257
E-mail : mpingo@tfs.go.tz
In reply please quote: TFS.297/ 402/01/61 08/09/2015

The Vice Chancelor

Sokoine University of Agriculture

P. O. BOX 3000 MOROGORO, TANZANIA

RE: PERMIT FOR *GREYSON Z. NYAMOGA* (Tanzanian) TO CARRY OUT RESEARCH IN INSTITUTIONS UNDER TANZANIA FOREST SERVICE AGENCY (TFS).

Please refer to the above subject and your letter with Ref: SUA/ADM/R.1/8 of June 16th 2015.

By this letter, *"Permit"* is hereby granted to GREYSON Z. NYAMOGA , (c/o Sokoine University of Agriculture) to conduct research in the institutions / forest reserves under Tanzania Forest Service Agency (TFS). The research title is *'Economic and Greenhouse Emission impacts of Changes in Forest Management, Land Uses and REDD+ Policies in Tanzania'.*

The permit is subject to the conditions prescribed hereunder.

1. Taking all reasonable precautions not to enter into conflict with forest staff/adjacent communities or create a situation thereof, in connection with the research operations.
2. At Researcher's own expense deposit at TFS Library in Dar es salaam, one copy of any publication of any sort and any other publicly available information arising out of or produced in connection with the research.
3. The permit is valid from 17th *June 2015* to 30th *December 2015.*

Lenia Mathias
For. CHIEF EXCUTIVE

c.c. The Researcher: GREYSON Z.NYAMOGA - c/o VC, SUA P.O.BOX 3000 MOROGORO
The Director General, COSTECH P. O. BOX 4302 DAR ES SALAAM
Zonal Managers, Tanzania Forest Service Agency – Please accord the researcher with due cooperation.

CLEARANCE PERMIT FOR CONDUCTING RESEARCH IN TANZANIA

SOKOINE UNIVERSITY OF AGRICULTURE
OFFICE OF THE VICE-CHANCELLOR
P.O. Box 3000, MOROGORO, TANZANIA
Phone: 023-2604523/2603511-4; Fax: 023-2604651

Our Ref. SUA/ADM/R.1/8/ Date: 16th June 2015

TO WHOM IT MAY CONCERN

Re: UNIVERSITY STAFF, STUDENTS AND RESEARCHERS CLEARANCE

The Sokoine University of Agriculture was established by Universities Act No.7 of 2005 and SUA Charter of 2007 which became operational on 1st January 2007 repealing Act No.6 of 1984. One of the mission objectives of the University is to generate and apply knowledge through research. For this reason the staff, students and researchers undertake research activities from time to time.

To facilitate the research function, the Vice-Chancellor of the Sokoine University of Agriculture (SUA) is empowered under the provisions of SUA Charter to issue research clearance to both, staff, students and researchers of SUA.

The purpose of this letter is to introduce to you **Mr. Greyson Z. Nyamoga** a bonafide PhD student at the Norwegian University of Life Sciences (NMBU) and also an employee of SUA. By this letter **Mr. Greyson** has been granted clearance to conduct research in the country. The title of the research in question is **"Economic and Greenhouse Emission Impacts of Changes in Forest Management, Land Uses and REDD+ Policies in Tanzania".**

The period for which this permission has been granted is from **17th June, 2015 to 30th December 2015.** The research will be conducted in **Selected Regions in Tanzania.**

Should some of these areas/institutions/offices be restricted, you are requested to kindly advice the researcher(s) on alternative areas/institutions/offices which could be visited. In case you may require further information on the researcher please contact me.

We thank you in advance for your cooperation and facilitation of this research activity.

Yours sincerely,

Prof. Gerald C. Monela
VICE-CHANCELLOR

Copy to: Student – **Mr. Greyson Z. Nyamoga**

VICE CHANCELLOR
SOKOINE UNIVERSITY OF AGRICULTURE
P. O. Box 3000
MOROGORO, TANZANIA

HALMASHAURI YA MANISPAA MTWARA – MIKINDANI
(Barua zote kwa Mkurugenzi wa Manispaa)

Anuani ya Simu: MTWARA — Ofisi ya Mkurugenzi Manispaa Mtwara
Simu nambari. 023-2333102 — S.L.P. 92
Fax Na: 023-2334794 — **MTWARA**
Email- mtwaramkindani@yahoo.com

Kumb. Na.MM/MC/A.6/49/89 24/08/2015

Afisa Watendaji Kata za
- Kata ya Shangani
- Kata ya Reli
- Kata ya Vigaeni
- Kata ya Tandika

Kata ya Magomeni
MTWARA-MIKINDANI.

YAH: KUMTAMBULISHA BW. GREYSON Z. NYAMOGA

Mtajwa hapo juu ni mtumishi wa Chuo Kikuu cha Kilimo cha Sokoine .

Anafanya utafiti unaohusu ***"Economic and Greeenhouse Gas Emission Impact of changes in Forest Management, Lands Uses and REDD +Policies in Tanzania"*** Namtambulisha kwenu ili aweze kupata taarifa anazohitaji.

Aidha ni mategemeo yangu kuwa mtampatia ushirikiano wa kutosha ili kufanikisha suala lake la utafiti kwa maslahi ya taifa.

Donald L. Nssoko
K ny: Mkurugenzi wa Manispaa
MTWARA-MIKINDANI

For: MUNICIPAL DIRECTOR
MTWARA - MIKINDANI
P.O. Box 92
MTWARA

Nakala: Mkurugenzi wa Manispaa - (Aione ndani ya jalada)
MTWARA-MIKINDANI

JAMHURI YA MUUNGANO WA TANZANIA
HALMASHAURI YA MANISPAA DODOMA
(Barua zote zipelekwe kwa Mkurugenzi wa Manispaa)

MKOA WA DODOMA — Ofisi ya Mkurugenzi wa Manispaa
S.L.P.1249
Tel.: 2354817/2321550 — Dodoma
Fax: 2321550 — E-mail: dodomamunicipality@yahoo.co.uk

Unapojibu tafadhali taja:

Kumb. Na.HMD/T.40/6/VOL.11 Tarehe: 17/08/2015

Mkuu wa Chuo,
Chuo cha SUA
S.L.P 3000
MOROGORO

YAH: KUFANYA ~~MAZOEZI KWA VITENDO~~/UTAFITI

Tafadhali rejea somo hapo juu.

Napenda kukujulisha kuwa ombi lako la mwanachuo/~~wanachuo~~ wako GREYSON Z. NYAMOGA limekubalika.

Mtajwa afike Ofisi ~~ya~~ Zipatazo 12 za Kata kwa ajili ya kuanza ~~mazoezi~~ hayo/kufanya utafiti huo kwa tarehe husika. Aidha Manispaa haitakuwa na fungu lolote la kumlipa/kuwalipa mwanachuo/wanachuo huyo/~~hao~~.

Nakutakia kazi njema.

Kny: MKURUGENZI WA MANISPAA,
DODOMA

MKURUGENZI WA MANISPAA DODOMA

Nakala: Mkuu wa Idara/~~Kitengo~~ MAZINGIRA
Mwanachuo Ndugu: GREYSON NYAMOGA
Mtendaji wa Kata/Kijiji/~~Mtaa ya~~ WOTE WATAKAOHUSIKA

2B: Permits from different Authorities for conducting research works and studies in Tanzania and USA

Oregon State University

Department of Forest Engineering, Resources and Management
Oregon State University, 280 Peavy Hall, Corvallis, Oregon 97331-5706
Tel: 541-737-4952 | Fax: 541-737-4316 | http://ferm.forestry.oregonstate.edu/

Greyson Zabron Nyamoga
PhD Student Forest Economics
Norwegian University of Life Science
Dept. of Ecology and Natural Resource Management
P.O. Box 5003, 1432 Ås Norway

Dear Mr. Greyson Zabron Nyamoga,

I am pleased to invite you to spend six months with us, between January 1, 2016 and June 30, 2016. The Department of Forest Engineering, Resources and Management will provide shared office space and telecommunications access. In addition you will receive a Courtesy appointment that gives you library privileges and access to other university facilities and services pertinent to your appointment. You will be responsible for any computing network charges, ranging up to $150 a month depending on your needs.

You will be working directly with me but will have the opportunity to interact with other faculty in the College of Forestry. Your research interests relate to the potential role of forests and wood products in climate change mitigation, with emphasis on REDD+ and other policies in Tanzania. Our own research on the forest sector models is also concentrated in that area at present, so we will have many opportunities for interaction and collaboration. Upon arrival here, you will have collected the data necessary to build a forest sector model for Tanzania, using a Norwegian model as template that again is built upon our models for Oregon and the Pacific Northwest. As these models, the Tanzanian model will include detailed data on forest growth and ranges of forest management options in order to fully capture the forest sector's potential roles for climate change mitigation.

The main objective with your stay here will thus be to incorporate the simulations of forest growth and management with the timber and wood products market model to fully integrate the Tanzanian forest sector in one framework. As I have worked extensively with forest sector models (The American forest and agricultural model FASOM-GHG, various models of the Pacific Northwest, the NorFor model of Norway and now a new forest sector model for the US) and exactly with this type of incorporation of forest simulations, I am very familiar with software for this purpose and have substantial experience to share with you. I therefore believe that your visit will be advantageous for your PhD project.

If feasible, we would also appreciate your giving a seminar on a topic of your choice sometime during your visit. We find that to be a great way to expand our understanding of international forestry.

We are looking forward to your visit and the opportunity to exchange ideas about climate change and forests.

Gregory Latta
Oregon State University
Department of Forest Engineering, Resources, and Management
204 Peavy Hall
Corvallis, OR 97331
Telephone: 541-737-6264
E-mail: greg.latta@oregonstate.edu

JAMHURI YA MUUNGANO WA TANZANIA
OFISI YA WAZIRI MKUU
TAWALA ZA MIKOA NA SERIKALI ZA MITAA
HALMASHAURI YA MJI MAFINGA
(BaruazotezitumwekwaMkurugenziwaMji)

Simu: 026- 2772393
Fax :026- 2772070
Baruapepe:dedmjimaf@yahoo.com

OfisiyaMaliasiliMji,
S.L.P. 76,
MAFINGA.

KUMB. NA. HM/MAF/D.30/1/01 ***25/09/2015***

Kwa yeyote Anayehusika

(Wakurugenzi/Mameneja wa Viwanda na taasisi mbalimbali)

YAH: UTAMBULISHO WA NDUGU GREYSON Z. NYAMOGA KUTOKA CHUO KIKUU CHA KILIMO (SUA) WA KUFANYA UTAFITI KATIKA VIWANDA VYA KUCHAKATA MAGOGO MJINI MAFINGA

Husika na kichwa cha habari hapo juu.

Mtajwa hapo juu amefika katika ofisi ya Mkurugenzi wa Halmashauri ya Mji wa Mafinga kwa ajili ya utambulisho wa kufanya utafiti katika viwanda vya mbao na nguzo, misitu ya hifadhi,misitu ya kupandwa na taasisi mbalimbali.

Kwa barua hii ofisi ya maliasili Halmashauri ya MJi wa Mafinga inaomba mmpatie msaada unaostahili ili aweze kufanikisha zoezi hili katika kuendeleza tafiti zake za kimasomo. Utafiti huu utachukua takribani miezi sita(6) kuanzia 17 Juni 2015 hadi 30th . Disemba 2015.

Nakutakia utekelezaji mwema.

AFISA MALIASILI
HALMASHAURI YA MJI
S.L.P. 76 MAFINGA

Peter E. Kibona
Afisa Maliasili Halmashauri ya Mji
Mafinga

Nakala;
Mkurugenzi wa Halmasshauri- Aione kwenye Jalada

NMBU

Norwegian University of Life Sciences
Faculty of Environmental Science and Technology
Department of Ecology and Natural Resource Management (INA)

Our ref.	Your ref.	Date
Bs/May26-15		26.05.15

TO WHOM IT MAY CONCERN

PhD FIELDWORK CARRIED OUT BY MR. GREYSON Z. NYAMOGA

The aim of this letter is to introduce Mr. Greyson Nyamoga who is an Employee of Sokoine University of Agriculture, the Department of Forest Economics. Mr. Nyamoga is currently pursuing his PhD studies in Norway at the Department of Ecology and Natural Resources Management (INA), Norwegian University of Life Sciences (NMBU).

According to NMBU's regulations, all PhD students have to conduct research works and produce original findings in their field of study. For this purpose his research works will be conducted in Tanzania. The title of his PhD project is ***Economic and Greenhouse Gas Emission Impacts of Changes in Forest Management, Land Use and REDD+ Policies in Tanzania.*** The main objective is to develop a forest sector model for Tanzania and use it for analyses of economic and greenhouse gas emission impacts of forest management and policy changes. The model requires intensive data collected from different sectors and places. Among other offices, Mr. Greyson will have to visit government offices (Ministry of Natural Resources, Energy, Trade, Revenue Authorities and Board of External Trade etc), non-governmental organization offices, plantations (Sao Hill, Green Resources, KVTC etc) and many of the other private owned companies engaged in the forest sector economy in Tanzania.

We therefore ask for your kind assistance in the collection of the required data within your organisation. We ensure that all data collected will be treated with the highest confidentiality, and that the data will be used only in aggregated form in our analysis so it can not be identified to single enterprises. As stated earlier

P.O. Box 5003
NO-1432 Ås, NORWAY

www.nmbu.no
post@nmbu.no

+47 67 23 00 00

NMBU

the focus of the research is on **economics, greenhouse gas emissions, land use changes, forest management practices and REDD+ policies in Tanzania**. Since the model developed is for the whole forest sector in Tanzania, Mr. Nyamoga will have to visit almost all regions in Tanzania.

The time frame for his data collection is from **1st June 2015 to 30th December 2015**

Please, do not hesitate to contact the Department of Ecology and Natural Resource Management (INA) at the Norwegian University of Life Sciences in case you need furher clarifications, or the Department of Forest Economics, Faculty of Forestry and Nature Conservation at Sokoine University of Agriculture.

Thank you very much for your cooperation.

Yours sincerely,

Sjur Baardsen, Prof. Dr.
(Head of Department)
Email: sjur.baardsen@nmbu.no

Birger Solberg, Prof. Dr.
(Main Supervisor)
birger.solberg@nmbu.no

NMBU Norwegian University of Life Sciences

2C: A letter requesting for export and import data from Tanzania Revenue Authority (TRA)

SOKOINE UNIVERSITY OF AGRICULTURE
FACULTY OF FORESTRY & NATURE CONSERVATION
DEPARTMENT OF FOREST ECONOMICS
P.O Box 3011, CHUO KIKUU, MOROGORO, TANZANIA.

My Ref: FOF/Nyamoga//01

Date: 08 September 2015

Commissioner- Customs & Excise Dep
Tanzania Revenue Authority
P.o Box 9053
Head Quarter
Dar es Salaam

COMMISSIONER FOR CUSTOMS AND EXCISE
RECEIVED
DATE: 08/09/2015

Re: REQUEST FOR EXPORT AND IMPORT DATA FOR FOREST PRODUCTS IN TANZANIA

Kindly refer to the above heading.

My name is Greyson Zabron Nyamoga, a PhD Student at the Norwegian University of Life Sciences (NMBU) Norway but also an employee of Sokoine University of Agriculture (SUA), Morogoro, Tanzania.

I am currently doing my field works in Tanzania with the aim of developing a Partial Equilibrium Forest Sector Model for Tanzania. The model needs many inputs and outputs data for Forest Industry, factories and the entire forest sector in general. Among other information, I need data for import and export of Forest Products in the Country. I will appreciate to get these data for the past 5 consecutive years or 10 consecutive years if possible (i.e. from 2005 – 2015)

I thank you in advance.

Yours sincerely,

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Paper I

Chapter 8
Potentials for Rehabilitating Degraded Land in Tanzania

G.Z. Nyamoga, H.K. Sjølie, R. Malimbwi, Y.M. Ngaga and B. Solberg

Abstract In Tanzania, land rehabilitation seems promising for repairing damaged ecosystems and provide sustainable supply of forest and food products, thus securing vital environmental services including increased carbon sequestration for global climate change mitigation. Comprehensive estimates of how large areas Tanzania has of degraded land are however lacking. This study aimed to (i) assess the area of degraded land potentially available for rehabilitation in various regions of the country, and (ii) give a review of main experiences and economic results gained in previous land rehabilitation studies in the country. Based on new data from the National Forest Resource Monitoring and Assessment of Tanzania we found that about 49 % (43.3 mill ha) of the total land area in Mainland Tanzania is under either light (43 %, 37.7 mill ha), moderate (5 %, 4.4 mill ha) or heavy (1.3 %, 1.2 mill ha) erosion. These areas are substantial, and imply large opportunities for land rehabilitation. None economic studies were found which have calculated benefits and costs of land rehabilitation in Tanzania. Such studies are

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© Springer International Publishing AG 2016

R. Lal et al. (eds.), *Climate Change and Multi-Dimensional Sustainability in African Agriculture*, DOI 10.1007/978-3-319-41238-2_8

urgently needed in order to identify and prioritize among the most promising rehabilitation activities.

Keywords Deforestation · Reforestation · Afforestation · Agroforestry · Livelihoods · Land degradation · Ecosystem services · Community based, climate change · Income security · Sustainable land use · Economic benefits · Carbon sequestration · Soil erosion

8.1 Introduction

Tanzania experiences large land use changes. Between 2002 and 2012 the settlement and protected land increased by 26.7 and 8.5 % respectively, whereas wood and non-woody production land declined by 23.8 % and scattered settlement areas and agriculture land decreased by about 12.9 % (Malimbwi and Zahabu 2014). The area of degraded land is increasing, and land rehabilitation has been put forward as a promising path for repairing damaged ecosystems and secure ecosystem functions in order to enhance land productivity and provide essential goods and environmental services, including increased carbon sequestration for global climate change mitigation.

Forests supply about 92 % of the consumed energy in Tanzania through charcoal and firewood, as less than 15 % of the population, mainly in urban areas are connected to electricity (Mwampamba 2007). With a population increase of 2.7 % p.a. demand for wood and land is rapidly growing. About 55 % of the Tanzanian mainland is covered by forests (Malimbwi and Zahabu 2014; Tomppo et al. 2010, 2014), with an annual deforestation of about 3728 km^2, equivalent to 1.1 % of the total forest area (Bahamondez et al. 2010; Malimbwi and Zahabu 2014). Deforestation and land degradation due to over-exploitation and agricultural expansion leave the poor communities more vulnerable to poverty and causes multiple negative environmental effects (Appiah et al. 2009; Hartmana et al. 2014). Tanzania is among the 12 richest countries in the world with regard to biodiversity, in particular because of its forests (Myers et al. 2000). It has Africa's largest number of mammals, second largest number of plants, third largest number of birds, fourth largest number of reptiles and fourth largest number of amphibians (Burgess et al. 2002, 2007; Pettorelli et al. 2010).

Land degradation is a process of decline of natural resources due to improper practices and inability of the land to recover its natural state as results of disturbances of ecosystem functions (Bai et al. 2008; Bergsma et al. 1996; Rothman et al. 2007). Deforestation and land degradation is exacerbated by a range of factors like population growth, urbanization, rural-urban migration, overgrazing, types of land ownership, farming practices like shifting cultivation, slush and burn and monoculture practices and animal overstocking (Hartmana et al. 2014; Kajembe et al. 2005a; Mary and Majule 2009; Mbaga-Semgalawe and Folmer 2000). These agricultural activities result in reduced vegetation cover, decreased soil productivity, changes in species composition and severe soil erosion (Hartmana et al. 2014).

An important aspect here is the land ownership in Tanzania that is guided by the Land act and the Village land act of 1999 (Angelsen and Fjeldstad 1995; Shivji 1998, 1999). Under these two acts, land ownership can be under customary right of occupancy, granted right of occupancy, leasehold and residential occupancy rights. With poor land tenure systems and ownerships as well as deficient farming techniques, the agricultural land looses its fertility quickly forcing people to shift into new virgin and fertile lands.

Land rehabilitation is the process of repairing damaged ecosystems and ecosystem functions for the sake of raising ecosystem productivity to provide benefits to local people (Aronsod et al. 1993). These rehabilitation initiatives aims at restoring land to its original conditions by improving the soil and biodiversity conditions and forming a rational, effective and intensive land use pattern, increase effective cultivated land area and enhance land use efficiency (Angelsen and Fjeldstad 1995). If succeeding, rehabilitation can mitigate the need to shift to new areas hence reducing deforestation. Furthermore, rehabilitation activities are also accompanied by provision of multiple benefits such as sequestering carbon, improving food security and reducing poverty.

Despite the extensive deforestation and land degradation in Tanzania, to the best of our knowledge, very few if any studies exist on the potential to rehabilitate such lands in different land categories and regions of the country, and this study aims at filling parts of this void. The specific objectives of the study are to (i) assess the degraded land areas potentially available for rehabilitation in various regions in Tanzania, and (ii) give a review of main experiences and economic results gained in previous land rehabilitation studies in the country. Most efforts have been devoted to cover objective (i), where we provide information not published before from the newly established National Forest Resource Monitoring and Assessment of Tanzania (NAFORMA). We hypothesize that large areas are available for land rehabilitation in Tanzania, and that it is environmentally and economically viable to rehabilitate considerable parts of these areas.

The remaining part of the paper is organized as follows: In Chap. 2 the methods used for data collection are described, in Chap. 3 results and discussions are presented, and Chap. 4 provides conclusions and recommendations.

8.2 Methodology

The study is based on new data from NAFORMA and previous literature on socio-economic studies of rehabilitating degraded lands in Tanzania. Besides the review of articles, the websites of key organizations such as Tanzanian National Bureau of Statistics (NBS), Food and Agriculture Organization of the United Nations (FAO) and the World Bank (WB) were investigated. Information was likewise obtained from consultancy reports and personal communication with government officials and organization leaders to provide data about land rehabilitation projects undertaken by the government.

In the present study, NAFORMA has been essential for assessing potentials for rehabilitating degraded land in different land categories and regions in Tanzania, as the survey covers all regions and all main vegetation types of Mainland Tanzania (URT 2015; Tomppo et al. 2014; Vesa et al. 2010). The acquisition of NAFORMA data used a stratified systematic cluster sampling design (URT 2015; Tomppo et al. 2014; Vesa et al. 2010) considering estimation error and cost effectiveness. The sampling strata were located according to the distance between clusters and the number of plots within a cluster. Depending on the accessibility of the area, about 6–10 plots were established in each cluster. Data were collected from about 3419 clusters with a total of 32,660 plots. The distance between plots within a cluster was 250 m (URT 2015; Tomppo et al. 2014; Vesa et al. 2010).

We have used the data about erosion as indicator for land potentially available for rehabilitation. NAFORMA operates here with four erosion categories (URT 2015):

- *No* erosion—i.e. “No evidence of erosion”.
- *Light* erosion—i.e. “Slight erosion where only surface erosion has taken place”.
- *Moderate* erosion—i.e. “Erosion where mild gullies and rills are formed on the top surface of the soil”.
- *Heavy* erosion—i.e. “Areas which have deep gullies, ravines, land slips etc.”.

8.3 Results and Discussions

8.3.1 Degraded Land in Tanzania

8.3.1.1 NAFORMA Results

NAFORMA provides a lot of information, and we have just concentrated on the erosion data. Table 8.1 shows that in each region a significant size of the land area is affected by light erosion, followed by moderate and heavy erosion. Moderate erosion is more pronounced in Arusha (11 %), Iringa (10 %), Dodoma (9 %), Kilimanjaro (9 %), Kagera (9 %), Morogoro (8 %), Njombe (8 %), Tanga (7 %) and Ruvuma (7 %). Generally, about 49 % (43.3 mill ha) of the total land area in Mainland Tanzania is under either light (43 %, 37.7 mill ha), moderate (5 %, 4.4. mill ha) or heavy (1.3 %, 1.2 mill ha) erosion. These figures are substantial and imply large opportunities for land rehabilitation.

According to the national population census of 2012, Kagera and Arusha are among the regions with the highest annual population growth rates of 3.2 % and 2.7 % respectively, followed by Morogoro (2.4 %), Tanga (2.2 %), Dodoma (2.1 %) and Ruvuma (2.1 %) while Kilimanjaro, Iringa and Njombe have the lowest rates of 1.8, 1.1 and 0.8 % respectively (Tanzania 2012). Except for Dodoma, the rest of regions are found in more mountainous areas where other factors than population growth can be major causes for the experienced erosion—

Table 8.1 Extent of soil erosion in Tanzania distributed by regions, zones and erosion classification[a] (in ha and percentage of total land area)

Zones	Regions	Total land area (ha)	No erosion (ha, %)	Light erosion (ha, %)	Moderate erosion (ha, %)	Heavy erosion (ha, %)
Eastern	Dar es Salaam	150,745	90,451 (60)	53,717 (36)	5311 (4)	1248 (0.8)
	Morogoro	6,883,954	2,926,819 (43)	3,337,838 (48)	551,081 (8)	67,879 (1.0)
	Pwani	3,195,044	1,951,576 (61)	1,134,445 (36)	104,346 (3)	4677 (0.1)
Subtotal		10,229,742	4,968,846 (49)	4,526,000 (44)	660,738 (6)	73,803 (0.7)
Southern	Lindi	6,782,646	3,990,429 (59)	2,457,231 (36)	229,939 (3)	105,006 (1.5)
	Mtwara	1,794,089	933,321 (52)	771,830 (43)	74,532 (4)	14,364 (0.8)
	Ruvuma	6,335,334	3,450,650 (54)	2,370,111 (37)	417,215 (7)	97,265 (1.5)
Subtotal		14,912,070	8,374,400 (56)	5,599,172 (38)	721,686 (5)	216,635 (1.4)
Southern Highlands	Rukwa	2,166,572	1,091,288 (50)	964,313 (45)	88,910 (4)	22,042 (1.0)
	Njombe	2,197,169	1,043,671 (48)	899,995 (41)	175,259 (8)	77,845 (3.5)
	Iringa	3,453,407	1,692,785 (49)	1,306,373 (38)	328,241 (10)	125,914 (3.6)
	Mbeya	6,103,794	3,045,373 (50)	2,804,948 (46)	187,921 (3)	65,296 (1.1)
Subtotal		13,920,942	6,873,117 (49)	5,975,629 (43)	780,331 (6)	291,096 (2.1)
Central	Manyara	4,468,061	2,297,674 (51)	1,984,640 (44)	159,547 (4)	26,124 (0.6)
	Dodoma	4,181,412	1,681,043 (40)	1,987,238 (48)	383,986 (9)	129,146 (3.1)
	Singida	4,854,872	3,190,200 (66)	1,531,275 (32)	92,149 (2)	41,249 (0.8)
Subtotal		13,504,346	7,168,917 (53)	5,503,153 (41)	635,681 (5)	196,519 (1.4)
Lake	Mara	2,188,993	890,714 (41)	1,189,552 (54)	82,604 (4)	22,537 (1.0)
	Simiyu	2,344,077	1,499,860 (64)	752,691 (32)	57,632 (2)	33,894 (1.4)
	Mwanza	1,091,792	440,590 (40)	599,834 (55)	48,732 (4)	2636 (0.2)
	Kagera	2,526,237	683,880 (27)	1,575,018 (62)	237,196 (9)	30,124 (1.2)
	Geita	2,095,244	1,290,783 (62)	753,520 (36)	36,253 (2)	14,622 (0.7)
Subtotal		10,246,342	4,805,826 (47)	4,870,615 (48)	462,418 (5)	103,813 (1.0)

(continued)

Table 8.1 (continued)

Zones	Regions	Total land area (ha)	No erosion (ha, %)	Light erosion (ha, %)	Moderate erosion (ha, %)	Heavy erosion (ha, %)
Western	Tabora	7,592,764	4,109,529 (54)	3,370,599 (44)	89,632 (1)	23,003 (0.3)
	Shinyanga	1,853,143	1,227,797 (66)	574,694 (31)	36,292 (2)	14,360 (0.8)
	Kigoma	3,818,200	1,844,521 (48)	1,752,197 (46)	172,158 (5)	49,221 (1.3)
	Katavi	4,340,422	2,308,605 (53)	1,863,881 (43)	143,864 (3)	24,034 (0.6)
Subtotal		17,604,528	9,490,452 (54)	7,561,371 (43)	441,946 (3)	110,618 (0.6)
Northern	Kilimanjaro	1,249,964	621,355 (50)	494,883 (40)	114,404 (9)	19,228 (1.5)
	Arusha	3,821,292	1,386,870 (36)	1,876,091 (49)	425,106 (11)	133,094 (3.5)
	Tanga	2,809,417	1,295,337 (46)	1,318,183 (47)	185,180 (7)	10,567 (0.4)
Subtotal		7,880,673	3,303,562 (42)	3,689,157 (47)	724,690 (9)	162,889 (2.1)
Total		88,298,642	44,985 121 (51)	37,725,096 (43)	4,427,490 (5)	1,155,374 (1.3)

Source URT 2015: NAFORMA Biophysical Data and Report
[a]Soil erosion classification as defined in Chap. 2 of this article

like steepness, rainfall, soil and vegetation types. Although Dodoma region is located relatively in flat areas, the high erosion there may be due to severe droughts which have been common in the region for many years and the interactions between steep slopes, flatness and severe rainfalls. Dry conditions followed by heavy rainfall may also contribute to severe gully erosion in many places.

The high percentage of moderate erosion and heavy erosion in each region is also influenced by land use activities including logging and agriculture,—especially inappropriate farming practices like over cultivation and overgrazing (Cohen 2002). The high erosion rates experienced in Lindi may be due to emigration of pastoralists from other areas, especially the Sukuma and Masai. These people tend to settle in forested lands leading to severe deforestation and land degradation (Charnley 1997a, b). Furthermore, land use conflicts between pastoralists and farmers have been common in Morogoro and some parts of Tanga regions in the past 10 years. Poor land property regimes might have led to these conflicts leading to improper land use management hence the pronounced erosion in the areas.

Most of the regions experiencing highest erosion are also covered by miombo woodland. Other studies and empirical evidences from the field show that miombo woodland are subjected to severe harvesting for charcoal as well as clearing for agricultural activities (Hofstad 1997; Kajembe et al. 2005b; Luoga et al. 2000; Mwampamba 2007; Mbwambo et al. 2012).

Table 8.2 indicates that the two land-use categories Production forest (59 %) and Grazing land (60 %) are the main land-use categories having most eroded land relative to their land area. In the category of Production forests the distribution on light, moderate and heavy erosion classes is respectively 49, 8 and 2 % of the land area of the category, and about 1.98 mill ha is found to belong in the moderate and heavy erosion groups. The high rate of erosion in the grazing land category is most likely caused by the experienced uncontrolled movements of the pastoralists in the country, and is a strong indication of the need for land rehabilitation programs in this field.

Table 8.3 shows the erosion by vegetation types and we see that all vegetation types are affected by erosion although to varying degree. In forests, the Humid montane category has the highest erosion relative to other categorie's land area (61 % or about 530,000 ha having erosion), followed by Plantation (38 % or about 220 000 ha) and Lowland (37 % or about 660,000 ha). In Woodland, Scattered cropland has the highest relative erosion (76 % or about 1.9 mill ha). Light and moderate erosion is severe in the Humid montane forest (59 %), Woodlands (51 %), Grasslands (49 %), Cultivated agroforestry system (47 %) and in Other land uses (41 %), indicating significant land rehabilitation potentials. Delaying interventions and leaving these eroded areas unattended increase the economic losses in terms of crop yields, pasture quality, forest products and other woodlands (Misana et al. 2003). Changes in forest cover may also have strong impacts on biodiversity richness, water storage and supplies, carbon sequestration and climate regulation (Hansen et al. 2013).

The data obtained indicate rather strongly that there is a need to ensure that proper forest management practices are in place to safeguards the humid montane

Table 8.2 Extent of soil erosion[a] in Tanzania by land use[b] and erosion classification[a] (in ha and percentage of total land area)

Land use	Total land area (ha)	Types of erosion			
		No erosion (ha, %)	Light erosion (ha, %)	Moderate erosion (ha, %)	Heavy erosion (ha, %)
Production forest	19,807,566	8,200,141 (41)	9,724,176 (49)	1,493,086 (8)	388,402 (2.0)
Protection forest	9,384,775	5,639,694 (60)	3,143,094 (33)	504,690 (5)	97,296 (1.0)
Wildlife reserve	19,976,100	12,246,966 (61)	6,951,606 (35)	621,980 (3)	155,548 (0.8)
Shifting cultivation	5,844,356	2,640,180 (45)	2,950,033 (50)	202,498 (3)	51,645 (0.9)
Agriculture	20,219,956	10,425,878 (52)	8,896,612 (44)	726,792 (4)	170,674 (0.8)
Grazing land	9,161,425	3,715,878 (41)	4,565,264 (50)	633,026 (7)	243,456 (2.7)
Built-up areas	1,851,412	867,324 (47)	886,482 (48)	97,606 (5)	–
Other land uses	2,053,053	1,249,060 (61)	607,829 (30)	147,812 (7)	48,352 (2.4)
Total	88,298,642	44,985,121 (51)	37,725,096 (43)	4,427,490 (5)	1,155,374 (1.3)

Source URT 2015: NAFORMA Biophysical Data and Report
[a]Soil erosion classification as defined in Chap. 2 of this article
[b]Land use category as defined in NAFORMA Report—http://www.fao.org/forestry/17847/en/tza/

forests. Also in Woodlands, Bushlands, Grasslands, Bare lands and the Agroforestry systems land categories we see that tree planting programs could be of high interest for rehabilitating the already eroded and degraded lands. The Bare soils category on open lands might also include potential areas for rehabilitation through tree planting. In the Plantation forest category, tree gap-filling or replanting are examples of measures which can be undertaken to reduce and improve the area under light erosion. Tree planting has been suggested to be among the best techniques of increasing forest cover and may help in protecting and managing large areas of secondary forest or regrowth (Lamb et al. 2005).

Arusha, Kilimanjaro and Morogoro with high rates of moderate erosion are all regions with high opportunities for tourism businesses, having famous national parks and other types of tourist attractions. Continued erosion in these regions may cause significant damage to the existing infrastructures hence reduced income opportunities, implying negative impacts to the livelihood of people in those regions. Rehabilitation of degraded lands in those regions at early stages of the damage seems therefore of particular interest, both from economic and environmental point of view.

Table 8.3 Extent of soil erosion[a] in Tanzania distributed on vegetation types[b] and erosion classes (in ha and percentage of total land area)

Vegetation types	Total land (ha)	No erosion (ha, %)	Light erosion (ha, %)	Moderate erosion (ha, %)	Heavy erosion (ha, %)
Forest					
Humid montane	863,060	333,426 (39)	417,283 (48)	94,165 (11)	18,185 (2.1)
Lowland	1,740,987	1,084,587 (62)	562,103 (32)	73,760 (4)	20,537(1.2)
Mangrove	136,148	110,665 (81)	24,295 (18)	127 (0)	1061(0.8)
Plantation	573,382	352,694 (62)	186,416 (33)	30,832 (5)	3440 (0.6)
Sub-total	3,317,185	1,881,373 (57)	1,190,097 (36)	198,884 (6)	43,223 (1.4)
Woodland					
Closed (>40 %)	9,019,093	5,265,503 (58)	3,103,724 (34)	544,918 (6)	104,949 (1.2)
Open (10–40 %)	36,230,449	17,245,981 (48)	16,430,475 (45)	2,000,524 (6)	553,468 (1.5)
Scattered cropland	2,471,271	602,022 (24)	1,753,242 (71)	88,583 (4)	27,424 (1.1)
Sub-total	47,720,813	23,113,506 (48)	21,287,441 (45)	2,634,025 (6)	685,841 (1.4)
Bushland					
Thicket	938,847	734,939 (78)	181,248 (19)	15,194 (2)	7466 (0.8)
Dense	1,909,936	1,368,472 (72)	410,026 (21)	102,576 (5)	28,862 (1.5)
Scattered cultivated	1,183,258	576,410 (49)	525,444 (44)	66,711 (6)	14,693 (1.2)
Emergent trees	311,714	166,196 (53)	131,965 (42)	13,552 (4)	–
With emergent trees	316,734	237,201 (75)	61,644 (19)	15,980 (5)	1908 (0.6)
Open	2,682,269	1,390,003 (52)	1,087,750 (41)	167,026 (6)	33,690 (1.3)
Sub-total	7,342,757	4,473,221 (61)	2,398,077 (33)	381,040 (5)	86,619 (1.2)
Grassland					
Wooded	4,834,247	2,368,835 (49)	2,173,034 (45)	220,870 (5)	71,507 (1.5)
Bushed	438,000	253,602 (58)	139,293 (32)	34,940 (8)	10,164 (2.3)
Scattered cropland	559,625	287,194 (51)	224,501 (40)	24,423 (4)	23,507 (4.2)
Open	3,354,513	1,607,302 (48)	1,601,981 (48)	130,077 (4)	15,153 (0.5)
Sub-total	9,186,385	4,516,934 (49)	4,138,809 (45)	410,311 (4)	120,331 (1.3)
Cultivated land					
Agroforestry	1,300,338	353,878 (27)	869,196 (67)	77,264 (6)	–
Wooded crops	1,450,010	804,196 (55)	602,564 (42)	38,378 (3)	4872 (0.3)
Herbaceous crops	4,924,182	2,379,306 (48)	2,181,325 (44)	315,414 (6)	48,137 (1.0)
Mixed tree-cropping	134,658	48,817 (36)	55,316 (41)	27,910 (21)	2616 (1.9)

(continued)

Table 8.3 (continued)

Vegetation types	Total land (ha)	No erosion (ha, %)	Light erosion (ha, %)	Moderate erosion (ha, %)	Heavy erosion (ha, %)
Grain crops	9,670,874	5,560,203 (57)	3,847,191 (40)	186,997 (2)	76,483 (0.8)
Sub-total	17,480,063	9,146,400 (52)	7,555,592 (43)	645,963 (4)	132,108 (0.8)
Open land					
Bare soil	129,795	74,375 (57)	36,867 (28)	13,761 (11)	4792 (3.7)
Others					
Water, Swamp, Rock	3,125,253	1,779,313 (57)	1,118,212 (36)	143,505 (5)	80,614 (2.6)
Total	88,298,642	44,985,120 (51)	37,725,096 (43)	4,427,489 (5)	1155,373 (1.3)

Source URT (2015): NAFORMA Biophysical Data and Report
[a]Soil erosion classification as defined in Chap. 2 of this article
[b]Vegetation types as defined in NAFORMA Report—http://www.fao.org/forestry/17847/en/tza/

Although the economics losses due to erosion and land degradation are not quantified, the observed consequences to the communities and the nation as a whole are evident. Land rehabilitation projects should of course consider areas where erosion is a problem. However, in addition, thorough cost-benefit analyses are needed to prioritize between promising rehabilitation projects, as outlined some further in Sect. 8.3.2.

8.3.1.2 Other Data on Land Degradation

The NAFORMA data gives at present no information about changes over time as the survey has just had one “round” of registration. However, there are other studies from Tanzania which could indicate degree of land changes and deforestation rates. Hall et al. (2009) found that during the period 1955–2000 the rate of deforestation in the Eastern Arc Mountains increased as indicated in Tables 8.4 and 8.5. We see that the deforestation has varied rather much according to mountain block (Table 8.4) and according to ecological zones (Table 8.5), with highest deforestation in Lowland montane. Also, the data show that the deforestation rates in this area was higher during the period 1955–1975 than during 1975–2000.

Empirical evidence suggests that land use changes will continue in the coming decades because of the changes in causal factors such as population and demand for food and forest products (Swetnam et al. 2011). FAO (2010) reports that between 1990 and 2005 the category Forest in Tanzania decreased by about 15 %, the category Other wooded land by about 79 %, and that the two land categories together decreased by about 37 % (Table 8.6).

Table 8.4 The Eastern Arc Mountain blocks and rates of deforestation

Mountain block	Forest area (km^2)			1975–2000	
	1955	1975	2000	Change (km^2)	%
East Usambara	425	299	263	−36	−12.0
Mahenge	35	24	24	0	0.0
Malundwe	9	6	9	3	50.0
Nguru	–	313	297	−16	−5.1
Nguu	207	198	188	−10	−5.1
North Pare	36	27	26	−1	−3.7
Rubeho	652	532	477	−55	−10.3
South Pare	195	147	139	−8	−5.4
Udzungwa	1745	1402	1354	−48	−3.4
Ukaguru	200	181	167	−14	−7.7
Uluguru	338	321	279	−42	−13.1
West Usambara	579	348	323	−25	−7.2

Source Hall et al. (2009)

8.3.2 Experiences from Previous Land Rehabilitation Studies

8.3.2.1 More General Findings

In the past three decades, various projects have been established to combat land degradation problem especially in mountainous areas (Kajembe et al. 2005a). Initiatives being put in place to rehabilitate and conserve deforested and degraded land in different regions of Tanzania include HADO (Hifadhi Ardhi Dodoma), HASHI (Hifadhi Ardhi Shinyanga), HIMA (Hifadhi Mazingira), LAMP (Land Management Program), SECAP (Soil Erosion Control and Agroforestry Project) and HIAP (Handeni Integrated Agroforestry Project) projects implemented in Dodoma, Shinyanga, Iringa, Babati-Manyara, Lushoto and Handeni respectively (Table 8.7). The main goals of these projects were to help local communities

Table 8.5 Ecological zones and the rate of deforestation in the Eastern Arc Mountain

Zone	1955 (km^2)	1975 (km^2)	2000 (km^2)	Rate of change per year (%)	
				1955–1975	1975–2000
Lowland montane (200–800 m)	609	347	274	−2.84	−0.95
Sub montane (800–1200 m)	748	480	440	−2.25	−0.35
Montane (1200–1800 m)	1954	1649	1559	−0.85	−0.22
Upper montane (>1800 m)	1410	1309	1262	−0.37	−0.15

Source Hall et al. (2009)

Table 8.6 Forest and other wooded land changes in Mainland Tanzania

Forest land category	Area (1000 ha)			% Change
	1990	2000	2005	1990–2005
Forest	41,441	37,318	35,257	−14.9
Other wooded land	22,374	10,629	4756	−78.7
Forest and other wooded land	63,815	47,947	40,013	−37.3
Other land	24,544	40,412	48,346	−97.0
Total land area	88,359	88,359	88,359	
Inland water bodies	6150	6150	6150	
Total area of country	94,509	94,509	94,509	

Source FAO (2010)—http://faostat3.fao.org/download/F/FO/E (visited on 20/01/2016)

rehabilitate degraded land and ensure sustainable supply of woodfuel and fodder for livestock (Ghazi et al. 2005; Iddi 2002; Msuya et al. 2006) and ensuring sustainable environmental and land conservation.

These different projects resulted in mixed outcomes, for example the HADO project in Kondoa District rehabilitated only about 428 ha of land while the HASHI project in Shinyanga region rehabilitated about 350,000 ha of land using agro-forestry systems and participatory approaches involving local communities (Pye-Smith 2010). Experiences from these activities and other land use

Table 8.7 Soil and Land Conservation/Rehabilitation Initiatives and Projects in Tanzania

S/No.	Name of the project/initiative	Year
1.	Dodoma Region Soil Conservation Project (Hifadhi Ardhi Dodoma—HADO)	1973
2.	Rukwa Integrated Development Program	1985
3.	Shinyanga Soil Conservation and Afforestation Project (Hifadhi Ardhi Shinyanga—HASHI)	1986
4.	East Usambara Conservation and Agricultural Development Project	1987
5.	Kigoma Rural Integrated Development Program	1989
6.	East Usambara Catchment Forestry Project	1989
7.	Soil Erosion Control and Agroforestry Project (SECAP)	1989
8.	Environmental Conservation in Iringa (Hifadhi Mazingira Iringa—HIMA)	1990
9.	Land Management Program for Environmental Conservation (LAMP) in Babati District	1991
10.	Dodoma Village Afforestation Project (DOVAP)	1991
11.	Dodoma Land Use Management Project	1991
12.	Handeni Integrated Agroforestry Project (HIAP)	1992
13.	Tanga Coastal Zone Conservation and Development Program	1993
14.	Kilosa Environment Project	1994
15.	Kilimanjaro Environmental Conservation Management Trust Fund	1990
16.	Community Based Forest Management (Participatory Forest Management)	2000
17.	Tanzania Community Forest Network (MJUMITA)	2005

Source Schechambo et al. (1999), Personal Communication and Consultancy Reports interventions are reported in many studies (Abdallah and Monela 2007; Birch-Thomsen et al. 2001; Cleaver et al. 2010; Cleaver and Schreiber 1994; Dejene 1997; Dixon et al. 2001; Iddi 2002; Kajembe et al. 2005a, b; Lamb et al. 2005; Massao 1993: Mutuo et al. 2005; Msuya et al. 2006; Oba et al. 2008; Pye-Smith 2010; Reid et al. 2009; Schechambo et al. 1999). It is not possible in this article to cover all results reported in those studies, but the following points are in our opinion interesting findings from the studies regarding what are important factors to consider in land rehabilitation projects in Tanzania:

- The main causes of land degradation
- Land tenure system—property rights
- Rules and regulations for monitoring and governing land-use changes
- Local community involvement
- Education and awareness programs to enhance adaptive capacity of the local community
- Improved agricultural and forestry practices, including agro-forestry

In the following the latter two points—adaptive capacity and agroforestry—are elaborated some more. Adaptive capacity is an important aspect for local communities to cope with the effects of climate change at the local level (Cooper et al. 2008). Land rehabilitation can increase the adaptive capacity of local communities because it provides improved livelihood options through increased land productivity and income (Paavola 2008). However, the implementation and adoption of an effective land rehabilitation technique is affected by many factors including education level, perceptions of people of the problem, proper land tenure, tribe affiliation, gender, land location and size, labour availability and off-farm activities (Tenge et al. 2004). Also, expected increased utility and profit are the basis for adoptions of any innovation in the community (Mbaga-Semgalawe and Folmer 2000). Investing in education and awareness programs is therefore important for ensuring success on rehabilitating degraded lands, and the economic benefits associated with each rehabilitation technique should be studied and provided in order to motivate local communities and other stakeholders involved in the process.

Agroforestry, tree planting and reforestation practices as means of rehabilitating degraded lands have multiple benefits. First, agro-forestry can enhance agriculture profitability by increased crop yields due to fertilization and other effects of the trees. The trees provide supply of fodder, fibers and other forest related products demanded by the communities. These trees can provide alternative sources of energy and forest products hence reducing pressure on the existing plantations and natural forests. It can also contribute significantly to carbon sequestration and provide multiple benefits to farmers hence reducing their vulnerability and increase their adaptive capacity to climate change, as well as providing increased biodiversity conservation and economic benefits to the community (Daily 1995). By rehabilitating degraded lands, community members can also benefit from REDD+ initiatives, as the planted trees on the degraded lands will contribute to carbon sequestration and hence qualify for carbon payments according to the additional amount of carbon sequestered.

The integration of trees in farming systems is facing a number of constraints especially those related to economic and policy competition with the agricultural sector (Garrity et al. 2010, Linyunga et al. 2004). However, rehabilitating degraded croplands and pastures by converting it into a tree-based systems could increase the aboveground and belowground net carbon sequestration with about 10–70 Mg C ha^{-1} in the vegetation and 5–15 Mg C ha^{-1} in the topsoil within a period of about 25 years (Mutuo et al. 2005). The agroforestry tree-based systems is capable of sequestering carbon in vegetation up to more than 60 Mg C ha^{-1} compared to crop or pasture systems (Mutuo et al. 2005). In their opinion, rehabilitation of degraded land using agroforestry techniques is an important aspect with multiple benefits, including timber, wood fuel, soil nutrients, carbon sequestration and trade, reducing vulnerability, increasing adaptive capacity of people and reducing climate change impacts to local communities.

The multiple benefits obtained from the planted trees may therefore motivate local communities to participate in the rehabilitation process. With multiple tangible economic benefits it is possible to engage both private organizations and the government in rehabilitating degraded land. The government can promote rehabilitation activities by providing initial funding and awareness creation to local communities, profit and nonprofit organizations. Training, awareness creation and provision of startup funding can be potential motivation tools to local communities to increase the rate of adoption of the rehabilitation techniques.

However, to have a successful agroforestry system, it is important to understand land tenure and common practices of slash and burn agriculture which tend to affect tree planting and promotion of agroforestry practices. The complexity of causes behind deforestation and degradation and the importance of economic and policy frame conditions ask for combined efforts involving all relevant stakeholders such as individuals, private based organizations and the government.

8.3.2.2 Economic Results

To our surprise we were not able of finding any published economic cost-benefit analysis of land rehabilitation in Tanzania. However, several economic mechanisms, techniques and incentives for implementing effective rehabilitation programmes in tropical countries have been suggested. Paying the landowners for the ecological services and ensuring appropriate institutional, legal, and policy settings for providing defined land tenure systems and access to financial resources are among those mechanisms (Lamb et al. 2005). The growth of carbon markets for global climate change mitigation makes carbon sequestration a potential additional income to landowners (Montagnini and Nair 2004). They anticipate *op.cit.* that the extra income from the carbon trade could be an effective incentive to motivate local communities to undertake agroforestry practices and tree planting for land rehabilitation.

Forest goods and services support the economic livelihoods of more than 1 billion people, mainly in third world countries (Sunderlin et al. 2005). Both natural forests and plantations play a significant role in sustaining the livelihood of local communities. Products such as sawn wood, paper and fibre materials contribute directly to the economy, but also other goods derived from the forest ecosystems have significant economic value (De Groot et al. 2012). They claim that investments in afforestation and reforestation activities can potentially increase the value of forest related industry and carbon stored in forests notably. In many developing countries, wood is an important source of energy particularly in rural areas and at the same time providing raw materials for various forest related industries (Mwampamba 2007). Further, local communities collect different types of non-timber forest products (NTFP) from the forest for both domestic and commercial uses. These non-timber forest products have significant impacts to the livelihoods of households in some of the rural and peri-urban communities. In some communities especially in dry central parts of Tanzania, the NTFPs are the only source of food throughout the year. Forests also provide important services such as soil erosion control, biodiversity, catchment and watershed management, and protection of coastal areas. Forest produces wood fuels which can be used as an environmentally friendly alternative to fossil fuels in forms of biogas and bio-fuels (Ahlborg and Hammar 2014; Sheya and Mushi 2000; Van Eijck and Romijn 2008; Van der Werf et al. 2009). Other important forest benefits with potentially high economic values include tourism, biodiversity habitat protection, food sources, medicinal plants, forest products, regulation of the hydrologic cycle, protection of soil resources, recreational and spiritual benefits (Bonan 2008).

Carbon sequestration through afforestation projects and activities have proved to be a cost effective methods used for reducing carbon dioxide emissions (De Jong et al. 1997). More information on the availability of the potential lands for rehabilitation and carbon sequestration are however needed. According to De Jong et al. (1997), the estimation of costs for carbon sequestration may be simplified if proper information on land and land uses are available. Afforestation and reforestation activities may currently be cheap, but in the long run large-scale investment in these activities may encounter substantial cost increases because lands with higher productivity and opportunity costs must be used and transaction costs may increase (De Jong et al. 2000).

Lacking economic cost/benefit studies on land degradation/rehabilitation in Tanzania, we refer to Table 8.8 taken from Bojö (1996) to illustrate the economic losses caused by land degradation in some other African countries. The gross annual immediate loss and the discounted future loss reported there are the foregone benefits for not rehabilitating degraded lands. The analyses referred to there are based on many assumptions, but the results illustrate the high economic importance that land rehabilitation may have.

The literature indicates that the majority of the local communities practice shifting cultivation as an adaptive means of increasing and maintaining food security in their households (Dixon et al. 2001). Poor households consider deforestation rational because of the short-term benefits obtained. According to Gootee

Table 8.8 Economic loss due to land degradation in some African countries

Study	Country	Gross annual immediate loss (in million USD)	Gross discounted future loss (in million USD)	Gross discounted cumulative loss (in million USD)
FAO (1986)	Ethiopia	14.8	–	2993.0
Sutcliffe (1993)	Ethiopia	155.0	15.0	–
Bojö and Cassells (1995)	Ethiopia	130.0	22.0	2431.0
Convery and Tutu (1990)	Ghana	166.4	–	–
Bojö (1991)	Lesotho	0.3	3.2	31.2
World Bank (1988)	Madagascar	4.9–7.6	–	–
World Bank (1992)	Malawi	6.6–19.0	48.0–136.0	–
Bishop and Allen (1989)	Mali	2.9–11.6	19.3–76.6	–
MacKenzie (1994)	South Africa	18.0	173.0	503.0
Stocking (1986)	Zimbabwe	117.0	–	–
Norse and Saigal (1992)	Zimbabwe	95.5	–	–
Grohs (1994)	Zimbabwe	0.6	6.7	44.7

Source Bojö (1996)

et al. (2010) inadequate information on agricultural techniques and sustainable land uses and the increasing demand for forest products and agricultural land are the main reasons for the high rate of deforestation and land degradation by poor households. Thus, creating awareness and promoting adequate practices and systems are important for rehabilitating degraded lands in Tanzania. This will assist in mitigating climate change, enhancing adaptive capacity, providing tangible benefits to the communities and ensuring sustainable natural systems management (Alexander et al. 2011).

The majority of rural people in Tanzania rely on agriculture for their livelihoods. This is also common in many Sub-Saharan African countries where a large share of the world's poorest people are located. Without formulating and implementing proper measures, the available forests are likely to disappear even faster in the next few decades than experiencing now (Poore 2013). The limited available data on costs and income and lack of information on important benefits of forest conservation are among the serious problems facing people in making proper decisions on land rehabilitation methods (Angelsen and Rudel 2013).

The lack of analysis of the economic impacts of land rehabilitation in Tanzania is striking. Thorough cost-benefit analyses are strongly needed to prioritize between land rehabilitation projects. These analyses should emphasize to include all costs and benefits involved, and quantify them in economic terms as far as practically possible. Various techniques exist for that. However, some costs and benefits might be very difficult to quantify in economic terms, but in such cases one should at least try to quantify them in physical terms. An essential element in such analysis will be to quantify the distributional impacts—i.e. how costs, benefits and net surpluses—are distributed over time between different main stakeholders (e.g. poor and rich, local community, region, country at large).

8.4 Conclusions

Previously, only scant information was available on the extent and amount of land degradation in Tanzania, but now the NAFORMA data clearly show that the country is experiencing serious land degradation problems and where in the country they occur. The land degradations are exacerbated by significant increases in population, economic growth and demand of food and forest products.

These land use changes need proper attention to ensure sustainable supply of forest and food products and maintaining environmental benefits and services, including increased carbon sequestration. Appropriate measures to meet these changes may have significant implications to poor vulnerable households with weak adaptive capacities. Agroforestry and tree planting programs are potential techniques for rehabilitating degraded land in Tanzania because of the expected multiple economic and environmental benefits to the community and the country. Incorporating rehabilitation of degraded land through agroforestry, reforestation and other tree environmental protection activities is important also in order to benefit from the globally growing carbon markets.

Economic studies on the benefits and costs of land rehabilitation in Tanzania and their distribution on various stakeholders are urgently needed in order to identify and prioritize among the most promising rehabilitation activities.

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Paper II

A Review of Studies Related to Charcoal Production, Consumption, and Greenhouse Gas Emissions in Tanzania

Greyson Zabron Nyamoga and Birger Solberg

Abstract Production and consumption of charcoal play a significant role in enhancing the livelihoods of people in Tanzania but may also lead to adverse environmental impacts. In this chapter, a review is presented of studies of charcoal production and consumption in Tanzania, and promising new research tasks are identified. Many interesting and valuable studies have been done, and it is clearly seen how important charcoal consumption and production are in a social, ecological, and economic perspectives. However, many of the reviewed studies lack clear hypotheses and specifications of behavior theories to be used for developing realistic and testable hypotheses. More research is needed on factors effecting charcoal demand – like changes in prices, income, and policies – and for that, using national household surveys is recommended. More research is needed also about tree regeneration (time and volumes) in miombo woodlands; how various forms of land ownerships influence miombo woodlands management; the possibilities and preferability in Tanzania of establishing forest plantations for producing charcoal; total and distributional impacts of policies; GHG impacts of charcoal production and consumption; and the development of bio-economic models which make possible consistent analyses of ex ante defined interesting changes from the present economic and policy situation.

Keywords Bioenergy · Climate impacts · Agent behavior · Urbanization · Deforestation · East Africa

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Y. Bamutaze et al. (eds.), *Agriculture and Ecosystem Resilience in Sub Saharan Africa*, Climate Change Management,
https://doi.org/10.1007/978-3-030-12974-3_17

1 Introduction

1.1 Overview

In Tanzania and most sub-Saharan countries, biomass accounts for more than 70% of the consumed energy (Mwampamba 2007; Felix and Gheewala 2011; Schure et al. 2013; Lusambo 2016) with firewood and charcoal being the most common (Mshandete and Parawira 2009; Dasappa 2011; Al-Mulali and Sab 2012). High population growth and inefficient stoves escalate the demand of charcoal and firewood; and together with agricultural expansion, overgrazing, illegal logging, and improper land tenure systems lead to deforestation and forest degradation in rural poor communities (Hosier et al. 1990, 1993; Chidumayo 1993; Hofstad 1997; Chidumayo and Gumbo 2013).

In urban areas in Tanzania, charcoal is used by more than 80% of the population as the dominant source of energy for cooking (Zahabu 2010; Chidumayo and Gumbo 2013). The high demand of charcoal there is caused by demographic factors as well as its reliability and affordability compared to other energy sources (Martin et al. 2009; Felix and Gheewala 2011). The urban population of Tanzania constitutes at present about 32% of the country's total population and is growing at a rate of 7% p.a. (URT 2017a, b; NBS 2017 and WB 2018), whereas the total population of Tanzania is increasing at the rate of 2.7% p.a. The high charcoal consumption in urban areas, high population growth, and high urbanization rate are important factors for the future demand of charcoal in Tanzania and consequently for the country's wood extraction for charcoal production. At present about 55% of mainland Tanzania is covered by forests (Tomppo et al. 2010, 2014; Malimbwi and Zahabu 2014), and the annual deforestation is estimated at 3728 km^2, equivalent to 1.1% of the country's total forest area (Bahamondez et al. 2010; Malimbwi and Zahabu 2014).

Electricity, gas, or kerosene substitute for using charcoal in cooking in some cases. In 2007 less than 15% of Tanzania's population were connected to electricity (Mwampamba 2007). By 2016, according to REA (2015) and URT (2017a, b), about 33% of all households in mainland Tanzania were electrified, covering about 64% of the households in urban areas and 17% in rural areas. However, in Tanzania, electricity, kerosene, and gas are very expensive compared to charcoal, and their use is rather limited.

Charcoal production and consumption play a significant role in deforestation, land degradation, and economic livelihood in Tanzania. Many studies have been done to obtain increased knowledge about this role, but these studies differ with respect to factors like objectives, geographical coverage, sample size, methodology, and results obtained. It is thus of high interest to compare these studies and identify information mostly needed for improved land-use planning and policy making in Tanzania.

This study was undertaken against this background, and its main objectives were to (i) give an overview of previous studies of charcoal production and consumption in Tanzania with particular reference to documenting behavior theories, sample size and statistical methods applied, geographical area covered, and main results obtained and (ii) identify where improved data and research are mostly needed.

2 Methodology

2.1 *Selection of Publication and Data*

We applied Google Scholar as search engine for finding publications to be included in our study. The main selection criteria were (i) having charcoal in Tanzania as main element and covering at least one of the above stated sub-objectives; (ii) published in peer-reviewed research journals or in governmental or consultancy reports which are publicly available and are of sufficiently high scientific quality; and (iii) published after 1990. Regarding criterion (i) we made exceptions (in particular regarding studies on GHG emission) for a few studies which cover countries in East Africa or sub-Saharan Africa but are relevant also for Tanzania.

For each of the selected studies we focused on presenting methodology and main results. Regarding methodology, we emphasized on behavior theories assumed, geographical area covered, sample size, main variables studied and statistical method applied. Including behaviour theory in this overview was done because any statistical study of consumption or production to be realistic ought to be based – implicitly or explicitly – on factors which reflect on the behavior of the producers or consumers studied. Our search resulted in 16 articles published in peer-reviewed research journals and 5 governmental or consultancy reports, as shown in Table 1. Only very few studies relevant for Tanzania were found covering GHG emissions from charcoal production or consumption.

3 Results and Discussion

In Table 1 an overview of the main findings is presented for each of the reviewed studies. In the first column, the title and year of publishing are shown. In the second column, we show geographical coverage, sample size, whether statistical analyses have been done and if so which, if any behavior theory is used for justifying hypotheses, and the chosen explanatory variables applied in the statistical analyses. In the third column, the main results of the studies are presented, placing emphasis on quantified results but also including qualitative results which are found to be of particular interest. The information presented in Table 1 is self-explanatory in many respects. Because of space limitations, we therefore concentrate our discussion on charcoal consumption, charcoal production, the emission of Greenhouse Gases (GHGs), and, finally, a more general discussion.

Table 1 Summary of the main findings in selected publications regarding production, GHG emissions, and consumption of charcoal in Tanzania

No	Authors and article title	Methodology	Main results
1.	Hosier (1993) *Charcoal production and environmental degradation: Environmental history, selective harvesting and post-harvest management*	• No behavioral theory stated • Interviewed 180 charcoal producers and visited 19 production sites in Dar es Salaam, Mbeya, and Shinyanga region • Environmental degradation and wood recovery assessed based on *soil type, visible soil erosion, land use, cultivation, vegetation cover, land management practices, tree harvesting height, kiln damage and distribution of resprouting trees* • No statistical analysis done	• Selective harvesting, species mix, and growth are very important for natural forest management and regeneration • Post-harvesting management is an important policy measure for sustainable forest management and enhancing regeneration in the miombo woodlands • The woodland regenerations and time depend on the harvesting intensity and the disturbances • In most sites, nothing grew back in the site areas where the charcoal kiln was built • Fire management plays a critical role in determining woodland regeneration • Multiple burning and land exhaustion (extended agriculture and overgrazing) can rather much retard regeneration in the woodland by affecting soil fertility • Numerous agricultural clearance mixed with heavy grazing pressure and long-lasting erosion problem reduces the ability of the woodland resources to recover • Increased efforts are needed focusing on improving post-harvest management and efficiency of charcoal production in the areas located within the effective harvesting and transport distances • No regeneration times were quantified, but the author makes the observation that the miombo woodland has strong regenerative capacity and that some of the visited sites were reported by the village guides to have been harvested for charcoal production “three times in an individual’s lifetime”

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
2.	Hosier and Kipondya (1993) *Urban household energy use in Tanzania: prices, substitutes and property*	• Behavioral theory stated: *Economic theory of utility maximization* • Interviewed 1600, 620, and 450 households in Dar es Salaam, Mbeya, and Shinyanga, respectively, using structured questionnaire • Statistical analysis done • Variables used: (i) Dependent variable: *Energy consumed* (ii) Independent variables: *Income, household size, market price, effective price*	• Household energy consumption constituted about 80% of Tanzania's energy use • Electricity usage in Dar es Salaam, Mbeya, and Shinyanga were exclusively for lightning • The household consumption of charcoal per capita per year was 176 kg, 195 kg, and 245 kg in Dar es Salaam, Mbeya, and Shinyanga in the same order • Regarding firewood the annual per capita household consumption was 452 kg, 817 kg, and 784 kg for the same cities, respectively • During the 5-year period 1985–1990, 4.5% of the respondents reported that they had shifted from charcoal to another energy carrier (1.2% to electricity, 1.8% to kerosene, and 1.3% to firewood). But also 4% reported they had moved to charcoal use from another energy source (2% from firewood, 1% from kerosene, 0.6% from LPG), making the total consumption of charcoal unchanged during this 5-year period • Energy consumption did not differ by income, and electricity and LPG behaved as a normal good, while kerosene was an inferior good (consumption decreased with income) • Woodfuel behaved as a normal good in low-income groups and as an inferior good in a high-income category • Charcoal was the only main reliable source of energy in all the three selected cities • Electricity was found to be the cheapest energy source when calculated as price per gross energy unit delivered, and even when compared as cost per effective unit of energy, it was still the cheapest

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• Charcoal was found the cheapest energy source if improved cooking stove (*named Jiko*) was used, subsidies and duties are not included, and foreign exchange is accounted for, and firewood was the next cheapest • The author state that "Heavy reliance on modern fuels is the manifestation of misallocation of resources resulting from deviation of financial prices from the economic costs" • The energy ladder or energy transition theory is based loosely on the economic theory of household behavior and the assumptions that modern fuels are normal goods, while traditional energy are inferior goods • It is difficult for the energy ladder theory to work in Tanzania mainly because of large geographical differences regarding energy supply and the seasonal unreliability of electricity • Energy-poverty linkage do exist, but in Tanzania energy scarcity rarely causes poverty • Lifeline subsidy is recommended as the best policy option for poor households to afford modern energy types and hence reduce pressure on the forests. These households would rather go for fuelwood if no subsidy is available • Subsidy for kerosene seems more likely to help both the urban and rural poor to switch away from woodfuels • Household fuel mix seems the cheapest and best policy option for supplying energy at national perspective

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
3.	Boberg (1993) *Competition in Tanzanian woodfuel markets*	• No behavioral theory stated • No statistical analyses done • Backward linkage approach was used (*the path of the fuel was followed back from end user to the producers*) • Series of structured questionnaire surveys in 1990 interviewing 1600, 620, and 450 households in Dar es Salaam, Mbeya, and Shinyanga, respectively • In Dar es Salaam and Mbeya, a subsample of 10% of the respondents were randomly drawn for more detailed analyses, while in Shinyanga 7% were drawn • Field visit (excursion) was made to the selected production sites	• 75%, 79%, and 85% of the households in, respectively, Dar es Salaam, Mbeya, and Shinyanga used charcoal. For firewood the corresponding figures were, respectively, 17%, 59%, and 14% • Dar es Salaam residents consume more charcoal per capita per year (279 kg) than in Mbeya (215 kg) and Shinyanga (196 kg) • Regarding firewood the annual per capita consumption was 395 kg, 400 kg, and 104 kg for the same cities, respectively • Secondary traders have a great influence on the charcoal trade and are prevalent in all the three urban centers • Average charcoal and firewood transport distance was highest in Shinyanga (173 km and 105 km, respectively), followed by Mbeya (116 km and 20 km, respectively) and Dar es Salaam (102 km and 69 km, respectively) • The distance from producer site to nearest road was in all areas on average 5% of the total transport distance for charcoal and 15% of the total transport distance for firewood • Charcoal is transported exclusively by truck and lorries • The market for woodfuel in Dar es Salaam is competitive with many traders, wholesalers, and producers because there are many alternatives for transports than in other areas, while Mbeya and Shinyanga are dominated by a few large integrated wholesalers, transporters, and retailers • The demand for charcoal is relatively inelastic; hence traders in Mbeya and Shinyanga are flexible for raising charcoal prices

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Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• The margins for charcoal producers and traders varied between the three regions because they sell in different units and different market segments • In all the three regions, transport was the largest cost component (23–43% of retail price), surpassing the producer price • Taxes and fees summed to about 7–8% of the per sack retail price for charcoal, but a larger percent of these taxes were found not collected • The prices of the alternative energy sources are controlled, and the supply is often limited or inadequate leading to shortage and aftermarket sales at prices much higher than the official rates • Woodfuel supply systems in Tanzania are not well integrated, and a better integrated supply may increase efficiencies in coordination of transport and facilities for storing
4.	Monela et al. (1993) *Socio-economic aspects of charcoal consumption and environmental consequences along the Dar es Salaam-Morogoro highway, Tanzania*	• No behavioral theory stated (but it is mentioned that the price of charcoal drives its production and that deforestation near cities is caused by the profitable charcoal business at the expense of environmental protection) • No statistical analyses done	• Consumers believe that the greater the distance from the highway into the woodlands the better the charcoal • High-quality charcoal is believed to be *from tree species of the genera Terminalia*, *Combretum*, *Brachystegia*, and *Dalbergia* hence extensive deforestation in those areas with these species

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
		• Data collection: – Unstructured interviews of 750 charcoal traders using Ubungo charcoal checking point for Dar es Salaam and 250 charcoal producers randomly selected – Unstructured interviews of some electricity using households in Dar es Salaam to map electricity cooking costs	• During rainy season, less charcoal is produced since manpower is shifted to agricultural activities and also some charcoal kilns are not accessible at this time • The regeneration time of miombo forest to reach a harvestable size after selection felling is estimated to be about 35 years or more • Assuming 62% of the wood coming from high-stocked miombo woodland with an average growing stock of 45m^3 per ha and 38% of the wood coming from low-stocked miombo woodland with an average growing stock of 10 m^3 per ha and that it takes 7 m^3 of wood to produce 1 ton of charcoal, one gets an average use of forest land (deforestation rate) of 0.2208 ha per ton charcoal produced • Each of the 1177 households in the surveyed area who produced charcoal made an average of 36 kilns per year at an average production rate of 10 bags per kiln • With an average producer price of Tshs 95 per bag of charcoal this gave an annual income of Tshs 32,260. The average operational time per kiln was 10 days • A household of 5 people consumed on average about 21 bags of charcoal annually equivalent to about 0.6 tons • Total urban household annual expenditure for using charcoal was calculated to Tshs 12,160, while that of electricity was Tshs 12,193 • But charcoal was still preferred mainly because of the high investment costs of electricity stove and higher reliability of using charcoal

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
5.	Hofstad (1997) *Woodland deforestation by charcoal supply to Dar es Salaam*	• Economic behavioral assumed: 1. *Charcoal production is the result of profit maximization and is consumed in urban areas only* 2. *Charcoal consumption is a function of charcoal price, number of urban families, and average family income* • A theoretical demand/supply model study • Variables included in the model: distances, production costs, transport costs, prices, biomass quantity harvested, and size of areas deforested • No statistical analysis done	• Model results showed that charcoal price increased from Tshs 1800 to Tshs 1958 per bag in 10 years, while the supply area increased from 3416 to 6886 km^2, and harvest increased from 2.05 to 2.66 million m^3 per year • Degraded wedge will increase together with charcoal price until the steady state is reached when increment within the area is equal to consumption • The steady state is reached at a price of Tshs 3371 per bag and a degraded area of 91,518 km^2 • Land area used for charcoal production increases over time but at different rates depending on the population growth rates • The volume is not reduced to zero at any location because cost of wood collection then becomes prohibitive • As long as the cost of household energy through charcoal stays below that of kerosene, the price elasticity of charcoal demand is the most important factor on the demand side in affecting the rate of deforestation • Reduced demand for charcoal and shift to other forms of energy are the factors controlling deforestation but is only possible at high prices of charcoal causing consumers to shift to other forms of energy • An increase in the real price of charcoal is likely as a consequence of rapidly increasing urban population • It is argued that the income elasticity of demand for charcoal is likely less than one at present income levels; at higher-income levels, it may even be negative; and it is realistic to assume that the future charcoal demand will increase less than estimated in this study if urban household income grows in the future

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• Subsidizing the supply of substitutes (kerosene, electricity, or plantation-grown wood) may be an interesting policy measure
6.	Luoga et al. (2000a) *Subsistence use of wood products and shifting cultivation within a miombo woodland of Eastern Tanzania, with some notes on commercial uses*	• No behavioral theory stated, but the authors write that "The interactions between local communities, natural resource base, markets and the socio-political environment contribute to deforestation" • Data collected by structured interviews of 80 rural households in two villages in Morogoro Region • Systematic sampling of different wealth groups, age classes, and gender • Focused group discussion/ interviews with key informants • No statistical analyses done • Data were analyzed using descriptive statistics and content analysis	• 96% of the respondents used firewood for domestic fuel and 4% used charcoal • On average one household used about 162 ± 11 (SE) headloads of firewood per year, each weighing 29.2 ± 1.4 (SE) kg and having a volume of 0.048 ± 0.002 m^3, corresponding to 4730 kg and 7.8 m^3 of wood per year • The annual per capita firewood consumption was 1.5 ± 0.17 m^3 per year, implying an average of about 7.8m^3 for the household size of 5.2 persons • The durability of poles and hence the longevity of houses ranged from 3 to 15 years depending on the natural resistance of the poles to termites and other biodegraders • The woodland is important in subsistence farming where the cultivation of food crops goes along with collection of other food materials of fruits, edible tubers, and leaves from the woodlands • Shifting cultivation is common in the miombo woodland in Morogoro region – practiced by 68% of the respondents (*and probably this is similar to many parts of Tanzania*) • Timber for furniture and construction purposes and charcoal are the commercialized resources in the area • Charcoal was produced mainly for the markets in the urban areas of Dar es Salaam and Morogoro and was the most reliable cash-generating activity in the area

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• About 54% of the households were involved in charcoal production, but the participants move in and out of the business depending on the conditions • With five persons per household, four houses per household, and average house life span of 8 years, the per capita consumption of construction wood was 0.138 ± 0.01 m^3 per year • The volume used for subsistence purposes of fuels and housing then became 1.64 m3 per year per capita • The high price for the high-quality timber causes a shift to lesser known timber species for household items • A sack of charcoal weighing 35 kg was at USD 2.00 at kiln site, USD 2.50 at highway site, and about USD 5.00 to urban end consumers
7.	Luoga et al. (2000b) *Economics of charcoal production in miombo woodlands of Eastern Tanzania: Some hidden costs associated with commercialization of the resources*	• No behavioral theory stated explicitly, but the study is linked to economic theory of externalization • Structured and unstructured interviews of key informants in two rural villages 50 km East of Morogoro – 8 charcoal producers – 3 charcoal wholesalers – 3 village headmen – 3 forest guards – 1 regional forestry officer • 10 unburnt charcoal kilns were sampled for volume estimation • Focused group interviews	• High charcoal production in the area studied by using traditional earth mound kilns and household male labor • Labor is the major production input – all other costs at kiln site are negligible • On average it took 100 person days per kiln for making charcoal (including felling, log piling, kiln plastering, roofing, unloading of kiln, and loading sacks) • The standing wood volume of 16.7 m^3 cleared for charcoal production can produce 61 bags of charcoal ha^{-1}

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
		• No statistical analyses done	• On average a household of about 5 people constructed 5 kilns per year with each kiln requiring 10.2 ± 2.02 (SE) m^3 of wet wood and having a mean production of 1.2 ± 0.26 tons of charcoal equivalent to 44.2 ± 8.67 bags of charcoal (≈27.1 kg per bag). This means 8.16 m^3 of wood per ton of charcoal • 42 different tree species were used in the charcoal production • More than 56% of the harvested trees in the study area (ranging between 2.4 and 68.6 cm trunk diameter at breast height) were felled for charcoal burning • Sensitivity analysis indicated that charcoal business would still be profitable if more tax was paid by the charcoal producers • The profit realization and employment creation associated with charcoal production were high but accomplished at the expense of other potential uses of the woodland
8.	Sem (2004) *Supply/demand chain analysis of charcoal/firewood in Dar es Salaam and Coast Regions and differentiation of target groups*	• No behavioral theory stated explicitly • Questionnaire interviews of about 170 respondents • Direct field observation (field survey and visits) • Literature review of documented reports, information, and studies relevant to the study • Personal communications • Consists of two main parts – the first describing present woodfuel consumption, production costs, and main constraints in the supply/demand value chain and the second part providing information of efficiency, costs, and constraints of various types of stoves	• About 90% of the population in Dar es Salaam depends on charcoal as first choice of energy for cooking • The average daily consumption of charcoal in Dar es Salaam was estimated to be 2.8 kg per household or 24,000 bags per day, but only 10–20% of this amount passed through legal checkpoints • Reported average charcoal prices (in 2004) along the supply chain were – At production site 1000–1500 Tshs per bag – At nearest main road 1500–2500 " – At wholesalers in Dar es Salaam 4500 " – Retail price Dar es Salaam 5500 "

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
		• No statistical analysis done	• The main types of stoves used by urban dwellers are charcoal stoves and ovens, while rural dwellers use mainly firewood stoves dominated by inefficient traditional three-stone fireplace • Low-income communities located in rural and urban areas form a potential user group of charcoal and woodstoves • None of those low-income groups who are earning less than Tshs 45,000 per month was using electricity as main type of energy • Affordable stoves are those with prices ranging between Tshs 1350 and Tshs 5000 • By using improved charcoal stoves, the survey has recorded the savings among the users of up to 50 percent • The adoption level of improved stoves is higher in the urban households as compared to rural households • The simple traditional kilns are capable of making charcoal at a conversion rate ranging from 2 to 5.2 bags of charcoal from 1m^3 of fuelwood (*one study reported 2–3 bags and another one reported 2.84–5.20*) • Charcoal dealing is a purely male-dominated activity as no women dealers were found during the research period • A large potential is reported for improved institutional stoves to reduce fuel consumption in community centers and thereby reduce deforestation as well as health hazards • Improved institutional woodstoves designed at the University of Dar es Salaam and installed at some schools in Tanzania have indicated reduced fuelwood consumption, with fuel saving between 60% and 80%

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• Durability of the stoves is reported as the main aspect of concern among the interviewed persons and should be emphasized when planning future modifications
9.	Malimbwi et al. (2005) *Charcoal potential of miombo woodlands at Kitulangalo, Tanzania*	• No behavioral theory stated • Inventory Data at Kitulangalo Training Forest using 46 plots in the forest reserves and 30 plots in adjacent public land • All the plots were chosen by stratified random sampling	• Twelve species were found in the forest reserve, while eight species only were found in the public lands • The average volumes and basal areas per ha were 46.2 m^3 ha^{-1} and 7 m^2 ha^{-1} in public lands and 78.8 m^3 ha^{-1} and 10 m^2 ha^{-1} in forest reserve, respectively • The known suitable tree species for charcoal making in miombo woodlands, i.e., *Julbernardia globiflora* and *Brachystegia boehmii*, appeared to be abundant in the forest reserve and less available in public lands • The per ha volume and basal area increased with distance from the highway, while stem numbers per ha showed a reverse trend meaning that the woodland along the roadside had been depleted mostly for charcoal extraction due to easy accessibility compared with woodlands away from the highway • Average standing wood volume was 24.5 m^3 per ha and 56.5 m^3 per ha in, respectively, public land and forest reserve land • The mean annual increment (MAI) for the period of 3 years (1996–1999) was 2.35 m^3 ha^{-1} $year^{-1}$ • By using a conversion factor of 0.85 for fresh wood volume to wood biomass and kiln efficiency of 23%, the weight of charcoal that can be extracted from the woodland at the roadside was 0.29 m^3 ha^{-1} (fresh wood) × 0.85 × 0.23 = 56 kg of charcoal, equivalent to only one bag of charcoal

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• About 54 and 125 bags may be extracted at 5 km distance and from beyond 10 km from the highway, respectively • In the forest reserve, it will take about 23 years, 16 years, and 8 years for the woodland at, respectively, the roadside, 5 km and 10 km away from the highway to attain the forest conditions of 53.4 m^3 ha^{-1} of preferred tree species for charcoal making • In public lands, the recommended years to attain 35m^3 per ha standing volume is 15 years and 8 years, respectively, 5 km and 10 km from the roadside
10.	Monela et al. (2007) *Socio-economics of charcoal extraction in Tanzania: A case of Eastern part of Tanzania*	• No behavioral theory explicitly stated, but the study mention that *poverty, unemployment, urbanization, low prices and high demand are the main drivers of charcoal production and consumption* • Data collection: – Structured questionnaire used in interviewing 113 charcoal makers – Focused group discussion using a set of checklists – Participant observation • Statistical analyses done • Variable: (i) Dependent variable: *The amount (bags) of charcoal produced per month for sale* (ii) Independent variables: *Age, gender, education level, ethnic group, and number of wives*	• High rate of migration to charcoal production areas (along the Dar es Salaam and Arusha highways) • Twenty different tribes originating from different parts of the country were found in the study sites where charcoal is produced • Main economic activities are agriculture and charcoal production • Household members are the main source of labor for charcoal production • Main species favorable for charcoal production are *Julbernardia globiflora, Brachystegia boehmii, Tamarindus indica, Acacia nigrescens, Acacia gerrardii, Combretum adenogonium, Combretum molle, Combretum zeyheri, Combretum collinum, Diospyros kirkii, Xeroderris stuhrmanii, Mimusops kummel, Albizia harvey, Acacia goetzei* subsp. *goetzei, and Lonchocarpus capassa*

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• On average the producers got 3 bags of charcoal per tree felled, varying from 1.7 to 11 bags per tree • The average amount of charcoal produced for sale was about 354 bags (each about 28 kg) per household per year • Age, sex, and number of wives had statistical significant coefficients, hence impacts on charcoal extraction • Most charcoal producers used rectangular traditional charcoal kiln yielding about 29 bags of charcoal per kiln • Most of the charcoal produced were sold at the production site and in the production village where dealers from Dar es Salaam and other urban centers come to collect charcoal bags for their business • Price of charcoal was Tshs 1500/=, 1400/=, and 1000/= at roadside, village center, and kiln site, respectively • On average it used 40.6 days per kiln for wood cutting, kiln preparation, carbonization period, and unloading • For own consumption each household per year used on average about 100.3 headloads and 3.3 charcoal bags • About 67% of respondents indicated that charcoal is more scarce today than 10 years ago; at the same time, the tree cover was also found to be less today than 10 years back • Charcoal extraction in the woodlands is the most important economic activity providing employment and income to many households in both rural and urban centers • The high number of species preferred for charcoal extraction found in the study area is a clear indication of the available high potential for charcoal extraction

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• There is strong link between charcoal extraction and ecological balance of the woodland resource • Poverty is a compelling factor for the decision to engage in charcoal extraction • In the longer term, a costly and painstaking process of adopting improved technologies which require capital investment is unavoidable
11.	Van Beukering et al. (2007) *Optimization of the charcoal chain in Tanzania*	• The stated behavioral theories: 1. *Improved charcoal production can increase its sustainability* 2. *Profit maximization is the main motive for charcoal production* • 360 observations by interviewing different stakeholders • Data collected using semi-structured questionnaires, interviews, surveys, GIS, and value chain analysis • No statistical analyses done	• About 28% of the households are involved in charcoal production, earning between 71% and 81% of the household cash income • Charcoal producers make the least profit than other stakeholders along the charcoal value chain • Very low efficiency of the traditional kiln in the study area ranging between 10% and 20% • The total income from charcoal is estimated to be about 17.6 billion (USD 17.6 million) in 2005 • The commercial sector (small eating places, restaurants, small-scale industries, agro-processing industries {tobacco curing, tea drying, beeswax processing, etc.}) is estimated to use 31% of the total charcoal consumption in Tanzania, and the remaining 69% is for household consumption • While charcoal can be produced from a variety of different tree species, most of the trees used for charcoal are from the natural Miombo woodlands • Land use change around Kazimzumbwi area shows that plantation forest and cultivation with tree crops has increased considerably at the expense of natural forest and bush lands

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• Increased agriculture at the expense of forested areas in other parts of the catchments could be a major contribution to the effects seen in the area around Kazimzumbwi forest • Interviewed people confirmed that production of charcoal had done most damage to the forest • Due to relatively low efficiencies, a large percentage of fuelwood is diverted to GHGs like CO, CO_2, NO_x, and SO_2 • The ban from the government had little effect on charcoal production. Producers continued to manufacture charcoal despite the ban, and with traders loath to buy, stocks of charcoal increased in the production areas. After the ban, the increased demand from the consumers and little stock in the cities caused the producers to double the prices from the pre-ban level • The following main conclusions are drawn: – Because of its vast magnitude changes in the charcoal sector can only be realized gradually, sudden interventions such as a ban on charcoal production and trade are counter-effective – Despite high environmental awareness among the charcoal producers, their poverty leaves no alternative but continuing the profession of charcoal making – Projects improving the extremely low kiln efficiency would be beneficial both for local communities and the environment

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			– Payments for environmental services (PES) could be considered to reduce externalities – Current policies directed at the charcoal chain are inefficient in many ways. The command and control policies dominating the current government policies need to be supplemented by market-based approaches
12.	Mwampamba (2007) *Has the woodfuel crisis returned? Urban charcoal consumption in Tanzania and its implications to present and future forest availability*	• No behavioral theory stated directly, but the author links "*per capita charcoal consumptions with* per capita *income" and also "a high population growth and high reliance on charcoal as a major cause of environmental degradation*" • Households survey in six selected regions • 244 observations • Scenario analysis is done using population and consumption to project future charcoal demand to year 2100	• Per capita household consumption ranges between 3.12 and 6.01 bags per person per year (equivalent to 93.6–180.3 kg per person per year) • Low- and middle-income groups did not have significant effect on the amount of charcoal consumed • Increase in household size caused lower per capita consumption per household • High charcoal consumption in almost all selected regions (*Dar es Salaam*, *Mwanza*, *Morogoro*, *Mbeya*, and *Arusha*) with price variations between them • Mtwara and Zanzibar had the lowest per capita consumption • Lindi had the lowest price, while other towns in mainland Tanzania had almost the same price (Tshs 4683/bag) • The highest price was in Zanzibar where no or little production is taking place (Tshs 5280 per bag) • In the scenario analyses, 80% of the urban population are assumed to use charcoal for cooking • Important to reduce charcoal consumption by improving stove efficiency or kiln efficiency in the production • Promote alternative energy sources for cooking in Tanzania to reduce the negative impacts of charcoal production and consumption

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
13.	Malimbwi et al. (2007) *Situation Analysis of Charcoal Sector in Dar es Salaam: Charcoal Supply and Consumption*	• No behavioral theory stated • Data provided by – Literature review – Consultation with different experts – Stakeholders meetings with 20 institutions – Structured interviews of 288 households in Dar es Salaam in three different income classes • No statistical analyses	• 94% of the sampled households consume charcoal alone or mixed with other sources of cooking energy. As their first preferred fuel, 78% had charcoal, 13% had kerosene, 5% had electricity, and 4% had firewood • 28,759 bags of charcoal, 56 kg each, are consumed in Dar es Salaam every day – of which 22,526 bags are consumed by households; 4200 bags are used in hotels, bars, and vendors; 2000 bags are used in schools; 25 bags are used in hospitals; and 8 bags are used in the army • Assuming 19% energy conversion efficiency from wood to charcoal and weight/volume ratio of 0.85, it is reported that 3 million tons or 3.6 million m^3 of wood are needed annually to produce the 28,759 bags consumed daily in Dar es Salaam • From year 2001 to year 2007, there has been a shift in the household energy consumption in Dar es Salaam corresponding to a decline of 48% for kerosene, an increase of 4% for charcoal, and an increase of 50% for fuelwood (from 2% of total consumption to 4%), whereas the electricity part has remained unchanged • About 6800 bags of charcoal produced from the nearby regions enter Dar es Salaam each day • Traditional kilns have very low efficiency (11–30%) causing a significant loss of the wood biomass and energy • Significant amount of income is accrued from charcoal production

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• Both commercial and noncommercial transporters are involved in charcoal transportation • 70% of the charcoal consumed in Zanzibar comes from mainland Tanzania, amounting to 10,500 bags of charcoal per day. Of this 7500 bags are traded illegally • Degraded forest land within 300 km from Dar es Salaam should be forested properly and the wood used for charcoal production • Various policies with different implications were proposed in this study
14.	World Bank Report (2009) *Environmental crisis or sustainable development opportunity? Transforming the charcoal sector in Tanzania*	• No behavioral theory stated • Literature review • No statistical analyses • Excel-based simple bio-economic model developed for illustrating impacts of policy means regarding demand and supply of charcoal • Stakeholders workshops	• Charcoal the main source of energy in Tanzania even for the wealthier families in cities and urban centers • Tanzania consumes about 2650 metric tons a day totaling to about 1 million tons per year • Perceived low cost of charcoal and widespread availability is among the reasons for wide consumption in urban centers • The price of charcoal increased by 160% between 2004 and 2007 (retail price increased from Tshs 5000 to about 25,000/= between 2003 and 2008) • The value of the Tanzania charcoal is about US$ 650 million per year which is more than what is earned from cotton, coffee, and tea all together • The Tanzanian charcoal sector employs about 2 million people in the entire value chain (producers, truck transporters, bicycle transporters, large-scale wholesalers, and small-scale wholesalers), but the profit is more concentrated to transport agents and wholesalers

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• More efficient cooking stoves are considered important for reducing charcoal consumption in the country as well as reducing the price of the alternative energy sources mainly gas, kerosene, and electricity • A coherent policy framework governing charcoal production, trade, and use in Tanzania does not exist, and reliable statistic on the sector rarely exists • Various policies are presented based on Tanzanian conditions and experiences in other countries having a significant charcoal sector
15.	Msuya et al. (2011) *Environmental Burden of Charcoal Production and Use in Dar es Salaam, Tanzania*	• No behavioral theories stated • Used a simulation model (STELLA) doing mass balance accounting ecological modelling tool • Estimated charcoal consumption and forest loss using population growth as basis for the estimation	• Charcoal consumption in Dar es Salaam ranges from 1600 to 2200 tons per day causing a significant loss of forest due to charcoal production • Projected charcoal demand in 2009 in Dar es Salaam was 1904 tons/day totaling 694,960 tons per year • About 105,303 ha of forest are lost each year due to charcoal production for Dar es Salaam only totaling to about 150,433 ha nationwide • The annual charcoal consumption up to 2030 is projected to emit about 49.7 million tons of CO_2 • Emission of other GHGs will also be very high if no measure will be in place to minimize the emission • By 2030 more than 2.8 million ha of forest will have to be cut due to charcoal production for Dar es Salaam only
16.	Felix and Gheewala (2011) *A review of biomass energy dependency in Tanzania*	• No behavioral theory stated • A study based on literature review	• Charcoal and firewood are the main biomass energy sources for most households in both rural and urban areas and constitute 90% of all energy use in Tanzania

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• The total charcoal consumption in Tanzania was 750,000 tons annually in the year 2000 • Local wood consumption for charcoal in 2000 is in the study reported to be 222.37 million m^3, for a population of about 33 million people and average household size of 5 to 7 people, while firewood consumption is reported to be 55.5 million m^3 • The average charcoal consumption for each household was 30.05 m^3 and for firewood 7.5 m^3 • Charcoal is consumed by 94% of the households either alone or mixed with other fuels, and only about 6% of the households are estimated to not use charcoal • The use of energy-efficient charcoal stoves in Tanzania is minimal due to high initial installation cost that cannot be afforded by households with low income • Energy efficiency stoves for burning firewood and charcoal are not easily available in Tanzania due to the lack of government support and poor biomass energy policies • Charcoal has a higher calorific value per unit weight than firewood, which is about 31.8 MJ per kg of completely carbonized charcoal with about 5% moisture content as compared to about 16 MJ per kg of firewood with about 15% moisture content on dry matter basis • The overreliance on charcoal and the excessive use of firewood are the major causes of deforestation and land degradation of about 91,000 hectares of land annually

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• One way of reducing wood fuel consumption is to improve charcoal production techniques as well as charcoal cooking stoves in the households • More emphasis should be directed toward the use of energy-efficient charcoal and firewood stoves for cooking and the use of mixed fuel like liquefied petroleum gas (LPG) and biogas to reduce the burden on the forests
17.	Schaafsma et al. (2012) *Towards transferable functions for extraction of Non-timber forest products: A case study on charcoal production in Tanzania*	• Behavioral theory: Economic valuation of non-timber forest products • 1176 household observations from 4 different surveys done in earlier studies along the Eastern Arc Mountain (EAM) in Morogoro • These observations were put in a geographic information system (GIS) transfer modelling frame	• 80% of the interviewed households rely on agriculture as a main source of income • 94% of the sampled households uses firewood as a main cooking fuel, while 73% of the houses in the study were made of poles which mainly originate from the nearby forests • Households whose main source of income is from timber and NTFPs are more likely to produce charcoal • The available survey data suggest that 60% of the households producing charcoal use wood from protected forests and woodlands like protected areas and forest reserves, 20% from open access forests and woodland and 45% from farmland • The estimated total annual household production of charcoal from the EAM was about 2.9 million 30 kg bags (1.45 million 60 kg bags) equivalent to approximately 11% of the combined annual charcoal consumption in Dar es Salaam and the cities of Morogoro and Tanga, the main markets for charcoal from the EAM blocks • Prices vary from Tshs 4000 to Tshs 45,000 per 60 kg bag across the study area, with a mean price of Tshs 30,088 (USD 21) per bag in Dar es Salaam and Tshs 16,584 (USD 12) elsewhere

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• Several factors contribute to the variation of the market prices including distance from the market to Dar es Salaam (transportation costs), dummy for prices (to cover taxes, levies, and bribes and the year of data collection and inflation) • The total value of the annual extraction of charcoal from the EAM was approximately Tshs 21 billion per year in 2010 prices or USD 14 million, including charcoal sold as well as any charcoal consumed domestically
18.	Sander et al. (2013) *Enabling reforms: Analyzing the political economy of the charcoal sector in Tanzania*	• No explicit stated behavioral theories • Used political economy (PE) analysis and a so-called Net-Map tool to identify key actors and power networks prevailing in the charcoal sector in Dar es Salaam • Assessed the interactions between actors in the charcoal value chain in Tanzania • Used focus group discussions and key informant interviews • Interviewed 200 different stakeholders	• Tanzania charcoal sector is characterized by weak governance, limited low enforcement capability, and other regulatory capacity constraints • Comprehensive policies, strategies, and legal frameworks addressing charcoal sector are absent or missing • Overlapping responsibilities between different central government agencies are common in the country which in most cases are unnecessary duplicates performing similar or related duties • Charcoal production and trading is characterized by overlapping responsibilities between different central government agencies (Ministry of Natural Resources, Ministry of Energy, and the Vice President's Office under the Division of Environment, Prime Minister's Office, District Authorities, Village Authorities, TRA, etc.) • Most of the collected revenues (81%) goes to the National Authorities, and very little 17% and 2% are retained by the District and Village Authorities, respectively

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• Tanzania's charcoal sector does not function as envisaged in government strategies and policies due to the complex, formal governance framework of the charcoal sector in Tanzania and the associated incentives and disincentives • Well-known tax avoidance strategies are used to bypass formal sector regulations and to integrate government officials or institutions in an informal benefit sharing mechanism • The fiscal disempowerment of village and district governments creates substantial disincentives for formalization of the business and sustainable management of the charcoal sector • Lack of effective benefits sharing mechanism, unclear ownerships of forest assets, and low capacity of low enforcement are among the reasons for the loss of charcoal revenues at different levels • There is also lack of government control over charcoal business, and the only government-level authority linking and interacting directly with charcoal producers and traders is the village-level government • In many instances, one person tends to play many roles in the charcoal value chain, hence difficult to control them • There is a strong divergence between the de jure and de facto power relations between the government and other charcoal stakeholders • It is therefore vital to strengthen vertical accountability and exchange of information, engage charcoal dealers (producers, transporters, wholesalers) network, empower responsible institutions, and enhance regulatory transparency along the entire value chain

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• Reforming the charcoal sector in Tanzania requires a strong political economy consideration and willingness to change the illegal communication to formal and legal channels of information sharing
19.	Zulu and Richardson (2013) *Charcoal, livelihoods, and poverty reduction: Evidence from sub-Saharan Africa*	• No behavioral theory stated • Analyzes the linkage between charcoal production and poverty alleviation and the negative narrative that poverty is causing forest loss and environmental degradation • Explains the different dimensions of poverty *(material deprivation, voiceless and powerlessness, vulnerability and exposure to risks, poor education and health)* • The study is based purely on literature review • No statistical analyses	• Growing demand for charcoal has increased opportunities for income generation, rural livelihood support (from production and trading), and poverty alleviation • Charcoal production and trading pose different challenges including unsustainable production, environmental degradation, and negative health impacts for material-deprived households • The overexploitation of forest resources for charcoal production is mainly due to weak, misguided, neglected, underdeveloped, disjointed, overly prohibitive, contradictory, or nonexistent woodfuel policies and laws, combined with poor enforcement and regulatory capacity • The market for charcoal is described as dispersed, poorly developed, and weakly regulated • Charcoal economy is extensive and links to numerous enterprises and supports livelihoods in urban and rural areas • The primary actors in the charcoal value chain are *producers, wholesalers, retailers, and transporters* and *end users (consumers)* • Charcoal production and market plays a significant role in generating seasonal and full-time employment in regional value chains

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
			• Lower-income households generally consume more charcoal per capita; wealthier households also use charcoal • Lower-income households often pay a higher price per kilogram for charcoal because they buy it in smaller packages; wealthier households will typically purchase larger quantities for a lower price per kilogram • Rapid population growth, urbanization, and improved incomes are generally associated with decreases in firewood use and increases in charcoal consumption • For low-income households, both firewood and charcoal are assumed to be normal goods but are considered inferior goods for high-income households • Charcoal production increases vulnerability and exposure to risks by contributing to environmental degradation through deforestation, soil erosion, and increases in greenhouse gas emissions as negative impacts of poverty reduction • Charcoal production and trading undermining agricultural productivity by diverting male labor into charcoal production hence overburdening women on food crop production • The relationships between charcoal and poverty are very complex, and although there may exist positive relations, there are limits to charcoal-based poverty alleviation, and it therefore requires multifaceted and integrated approaches both on the production and demand sides

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
20.	D'Agostino et al. (2015) *Socio-economic determinants of charcoal expenditures in Tanzania: Evidence from panel data*	• No clearly stated behavioral theories, but the hypotheses are indirectly based on economic theory • Used two panel data sets collected in 2008/2009 and 2010/2011, with altogether 6367 household observations • Statistical analyses done • Variables used (i) Dependent variable: Household charcoal expenditure (ii) Independent variables: *Income, household size, location (rural and urban), and various dummy variables as so-called control variables* • Charcoal price is however not included as it is argued that it will be too uncertain to include	• Household income has a strong positive association with charcoal consumption, while household size does not • Rural households consume less charcoal than those located in urban areas • In the total sample with all control variable included, a 10% increase in total expenditure is estimated to be associated with 3.9% increase in charcoal expenditure, meaning an income elasticity of 0.424. This suggests that charcoal is a basic good • Panel data from Dar es Salaam indicates that household size is significant, and income elasticity there was estimated to be 1.11 • The estimated income elasticities varied according to which sample is used, being 1.11 in the sample which included only Dar es Salaam households (2178 observations), 0.69 in the sample having only urban households (82,178 observations), 0.39 in the total sample (6367 observations), and 0.32 in the sample where the households in Dar es Salaam were excluded (5322 observations) • For the betterment of the forests and the forest sector in general, policy makers should focus on finding sustainable alternatives and substitutes to replace charcoal • Targeting the urban centers is important because of the large effects income has on charcoal consumption in those areas

(continued)

Table 1 (continued)

No	Authors and article title	Methodology	Main results
21.	Nyamoga et al. (2019) *Econometric analysis of urban household charcoal consumption in Tanzania: The case of Morogoro, Dodoma and Mtwara*	• Based on economic theory • Data collected by structured questionnaire of 360 households randomly chosen in Morogoro, Dodoma, and Mtwara • Statistical analyses done for three income classes and the whole sample • Variables included (i) Dependent variable: *Charcoal consumption* per capita (ii) Independent variables: *Household income, charcoal price, price of other energy sources, household size, and geographical location*	• In the low-income group, statistical significant elasticities for annual charcoal per capita demand were found to be −0.40 and −0.60 for, respectively, charcoal price and household size • In the middle-income group, only household size was found significant with −0.83 as estimated elasticity • In the high-income group, elasticities of 0.20 for per capita income and −0.42 for household size were found significant • Statistically significant differences between regions were found in the low-income group and the whole sample. Price of electricity or gas did not become statistically significant variables. • The findings indicate that price of charcoal, household size, per capita income, and regional differences are key factors influencing urban charcoal consumption in Tanzania • The per capita charcoal consumption was significantly positive in the high-income group which contradicts with the so-called energy ladder theory • The study recommends further surveys (preferably a national survey) and research activities in other regions to investigate the long-run implication of charcoal production and consumption in the country. In this regards, masters and PhD students need to be involved intensively

3.1 Charcoal Consumption

Methodology

Sixteen of the 21 reviewed studies deal with charcoal consumption. Five of these studies include some kind of statistical analysis, but only three have stated some behavior theory to give hypotheses and guide for which variables to include in the statistical analyses.

Quantity

The estimates of charcoal quantities consumed per capita vary quite a lot. Boberg (1993) estimates the annual household per capita consumption in Dar es Salaam, Mbeya, and Shinyanga to be 280 kg, 220 kg, and 200 kg, respectively. Nyamoga et al. (2019) estimate the annual per capita consumption in Dodoma, Morogoro, and Mtwara to be 165 kg, 140 kg, and 145 kg, respectively, while the total average was 142 kg. Monela et al. (1993) estimate this consumption to be 117 kg for Dar es Salaam, whereas Malimbwi et al. (2007) estimate it to be 164 kg, and Hofstad (1997) assumes it to be 174 kg for Dar es Salaam. There are obviously many possible reasons for this variation in consumption estimates, like differences regarding sample selection, sample size, location, and questionnaire used, as well as different time and prices reflecting different supply and demand situations.

Two studies have estimated the use of charcoal in Dar es Salaam in the commercial and public sectors (hotels, bars, agro-industrial enterprises, schools, hospitals, army, etc.): Van Beukering et al. (2007) estimate that these sectors account for 31% of the total end use of charcoal in Dar es Salaam, whereas Malimbwi et al. (2007) estimate this share to be 22% (corresponding to a daily use of 4200 bags of charcoal from hotels, bars, and vendors, 2000 bags from schools, and 33 bags from hospitals and the army).

Prices

Van Beukering et al. (2007) observe that charcoal demand among commercial enterprises in Dar es Salaam is rather inelastic with respect to price. In a survey among these enterprises, most respondents claimed that they would continue to buy charcoal even if the price doubled. Van Beukering op cit. argue that this inelasticity of charcoal price can be directly related to the prices of alternative fuels and presents annual average fuel prices (measured as Tshs per Kcal energy produced) which show that in all years during the period 1995–2006, the price for charcoal in Dar es Salaam has been much lower than for kerosene, LPG, and electricity.

3.2 Charcoal Production

Methodology

Seven of the 21 reviewed studies deal with charcoal production. Of these, only Monela et al. (2007) include statistical analysis, with profit maximization referred to as behavior theory. Nearly all of the reviewed studies have a regional or local area focus. Different stakeholders are interviewed and the studies have from 8 to about 400 respondents. No national survey is found.

Quantities Produced

Several of the studies include interviews of kiln producers and analyses of their charcoal productions. Almost all of the charcoal production seems to be done with earth mound kilns having an energy recovery of 10–19%, meaning that 81–90% is wasted energy. The estimates of wood input requirement vary from $7m^3$ to $8.5m^3$ wood input per ton of charcoal produced.

None of the studies give estimates of charcoal export to or import from Tanzania, and presumably both might be small and/or counterbalance each other. Malimbwi et al. (2007) estimate that 70% of the charcoal consumption in Zanzibar comes from Mainland Tanzania, corresponding to 10,500 bags of charcoal per day, each bag weighing 53 kg, and that about 7500 bags are transported illegally.

3.3 Emission of GHG

Fuelwood consumption (firewood and charcoal) is among the critical environmental problems in many sub-Saharan countries including Tanzania (Sulaiman et al. 2017). It has been estimated globally that emission of greenhouse gases (GHGs) from biomass burning can exceed those emitted from fossil fuel-based GHG in many less developed countries (Bailis et al. 2003). To fulfil this fuelwood demand, tree cutting is necessary leading to significant deforestation and land degradation. The process of charcoal production can cause emission of different greenhouse gases including carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_2), SO_2, and methane (CH_4) (Bailis et al. 2003; Bailis 2009; Msuya et al. 2011; Chidumayo and Gumbo 2013). The emitted greenhouse gases, especially carbon monoxide and carbon dioxide, can be very poisonous and detrimental to the nervous and the brain system, resulting into severe illness and possibly death. The emitted nitrogen oxides, CO, formaldehyde, and carcinogens react with sunlight in the atmosphere leading into air pollution (ibid). It has been reported that the smokes produced from charcoal burning tend to augment those from diesel engines and industrial chimneys (NorConsult 2002). Msuya et al. (2011) report that charcoal production and consumption could lead to the production of about 50 million tons of CO_2 and more than 20 million tons of CO by the year 2030 and that about 9.8, 1.1, and 12.5 million tons of NO_2, SO_2, and CH_4, respectively, will be emitted by 2030 in Dar es Salaam alone, if the country continues using charcoal in the same way as today.

By using appropriate technologies, it is possible to reduce emissions from charcoal at both production and consumption points in the charcoal life cycle, through provision of high-efficiency and low-emissions charcoal stoves with improved combustion and heat transfer efficiency (Bailis et al. 2003). Except for Msuya et al. (2011), no studies from Tanzania were found of GHG emission related to charcoal consumption and production. We therefore have used FAO (2017) for getting more information here, and our best estimates for Tanzania are as shown below, assuming earth kiln in the production and Kenyan average charcoal stove in the consumption of charcoal. The uncertainty in these estimates is of course high.

1. Regarding emission from charcoal production, we assumed Kenyan earth mound kiln 2 with yield efficiency of 21.6% as stated in FAO (2017:151) and originally documented by Pennise et al. (2001), getting the following emission factors:

CH_4	35.2 kg GHG per ton of charcoal produced
CO_2	1992 kg GHG per ton of charcoal produced
CO	207 kg GHG per ton of charcoal produced
TNMHC or TNMOC[a]	90.3 kg GHG per ton of charcoal produced
N_2O	0.20 kg GHG per ton of charcoal produced
NOx	0.12 kg GHG per ton of charcoal produced
TSP	41.2 kg GHG per ton of charcoal produced

[a]*TNMHC* total non-methane hydrocarbons, *TNMOC* total non-methane organic carbon (Pennise et al. 2001)

2. Regarding emission from cook stoves, we assumed the average Kenyan charcoal stove as stated in FAO (2017:156) and originally documented by Bailis et al. (2003), getting the following emission factors:

CH_4	18 kg per ton of charcoal produced
CO_2	2280 kg per ton of charcoal produced
CO	260 kg GHG per ton of charcoal produced
TNMOC	3.2 kg GHG per ton of charcoal produced

In addition some GHG emissions from, e.g., transport and net GHG emissions from forest soils and biomass growth changes are also possible, but are not reported because the information here has not been found (not certain here, but this is what seems logical).

3.4 More General Discussions

Income Generation and Overexploitation

This review has revealed that charcoal production and consumption contribute significantly to the incomes of people in Tanzania and the rate of production along the miombo woodlands is increasing (Luoga et al. 2000a, b; Malimbwi et al. 2007) in spite of scarce literatures on its value chain. The increasing number of charcoal producers may be attributed to the free access to the miombo woodland and the low capital required for starting charcoal production among other factors. Although the investment in tree plantations for charcoal production is increasing in tropical regions including Tanzania, most biomass for charcoal production still comes from natural forests which tend to regenerate naturally (Chidumayo and Gumbo 2013). As the area of woodland decreases, the marginal value of each tree increases because the demand exceeds supply (Hofstad 1997; Luoga et al. 2000a, b). Most miombo woodlands are regarded as common pool resources, freely available to everyone. Therefore, the profit-maximizing individuals or households will continue producing charcoal as long as profit is maximized.

Despite the importance of charcoal for income generation in the households, inefficient production technologies such as the traditional earth kiln with very low efficiency of about 11–30% are used, leading to higher wood biomass consumption (Luoga et al. 2000a, b). With the low kiln efficiencies, about 70–80% of the wood are lost along the production process, signifying an increase in deforestation. Any innovation for improving kiln and cooking stove efficiencies may have a significant contribution in reducing the deforestation rates in Tanzania (Zein-Elabdin 1997; Sanga and Jannuzzi 2005).

Statistics indicate that Tanzania is among the top 10 global charcoal producers, producing about 3% of the world's total charcoal (FAO 2010). Rearranging and addressing holistically the entire value chain of charcoal can make charcoal production and consumption contribute to sustainable development and poverty alleviation in Tanzania (Neufeldt et al. 2015; Luvanda 2016). Provision of proper information on charcoal production and value chain would most likely help to identify possible opportunities for more efficient ways of organizing the charcoal markets and institutions arrangement for enhancing better returns to all stakeholders in the value chain (Shively et al. 2010). Empirical evidence from the field and previous studies indicate that charcoal production and consumption will dominate the energy sector for many years in sub-Saharan Africa (Hosier et al. 1990, 1993; Hosier 1993; Hosier and Kipondya 1993).

Charcoal production and the entire business in general have been perceived negatively because of the historical unsustainable production technologies employed. Due to unsustainable production techniques in Tanzania, charcoal production tends to be linked to deforestation and forest degradation, which in turn affects the livelihoods of people due to reduced land and ecosystem productivity (Jones 2002; Kissinger et al. 2012; Cerutti et al. 2015). According to Zulu and Richardson (2013), the overexploitation of forest resources for charcoal production is mainly due to weak, misguided, neglected, underdeveloped, disjointed, overly prohibitive, contradictory woodfuel policies and laws combined with poor enforcement and regulatory capacity. This is mainly due to the fact that most of the miombo woodlands in Tanzania are managed under general land with open and free access and subjected to many management challenges. The management challenges emerge because of the undefined land ownership that allows free access to the forest land and overexploitation (Schlager and Ostrom 1992). New regulations have been put in place for supporting sustainable charcoal production (Delahunty-Pike 2012). Charcoal production increases vulnerability and exposure to risk by contributing to environmental degradation through deforestation, soil erosion, and increase in greenhouse gas emissions (Kaimowitz 2003). This is an indicator that charcoal production and consumption can have both positive and negative impacts, like poverty reduction, deforestation, and land degradation. It may also undermine agricultural productivity by diverting male labor into charcoal production, hence overburdening women on food crops production. One of the reasons for charcoal production's contribution to deforestation is the use of traditional kilns with very low efficiency, which may require as much as 10 kg of wood for producing 1 kg of charcoal (Adam 2009). Besides demanding large amount of raw materials, these traditional kilns also release large amounts of greenhouse gases during the carbonization process. The efficiency problem also exists on the consumption side where the burning of charcoal in traditional cooking stoves is inefficient, resulting into increased wasteful consumption of charcoal as well as gas emissions inside houses, directly influencing peoples' health. Efficiency improvement is therefore an important aspect of both the production and consumption stages in order to reduce the negative effects (Sanga and Jannuzzi 2005; Adam 2009).

In Tanzania, cooking energy is dominated by biomass-based fuels and is primarily firewood and charcoal accounting for more than 90% of primary energy supply which is estimated at $1m^3$ of round wood per capita per year (Felix and Gheewala 2011; Lusambo 2016). The high preference for charcoal is due to its high calorific value per unit weight, which is about 31.8 MJ per kg of completely carbonized charcoal with about 5% moisture content compared to about 16 MJ per kg of firewood with about 15% moisture content on dry basis (Felix and Gheewala 2011). It is also preferred because of convenience in transporting, storing, and non-susceptibility to infections by fungi. Studies indicate that a household of about 5 people can consume 21 bags of charcoal annually which is equivalent to about 0.6 tons (Monela et al. 1993). Previous models developed by Faustmann and Hartman have suggested that harvesting of even-aged stand tends to be influenced by, among other factors, the opportunity costs for delaying the harvest and whether land owners pay management fee and property tax to government (Koskela and Ollikainen 2001; Chang and Gadow 2010; Deegen et al. 2011). The implementation of these models depends on factors like proper land ownership, forest characteristics, and vegetation types (Amacher et al. 2009; Kant and Alavalapati 2014) which are scarce in most miombo woodlands in Tanzania. The miombo woodlands are characterized by uneven-aged wood stands although charcoal and timber producers harvest the trees to maximize utility of the forest resources (Frost 1996; Luoga et al. 2002). Furthermore, unlike in developed countries, the amenity values for forest stands in Tanzania are less recognized by the local communities or does not exist at all; it is hence difficult to implement policy measures suggested by the models like those developed by Faustmann and Hartman.

The high demand for charcoal in Tanzania is mainly due to high human population growth, high rate of urbanization, and the high economic growth which in turn increases the population of the middle-income group that consumes charcoal in the urban centers (Malimbwi et al. 2007; Mwampamba 2007; Msuya et al. 2011). About 90% of the urban population depend on charcoal as the main source of energy for cooking (Hosier and Kipondya 1993; Hosier et al. 1993; Mwampamba 2007; Lusambo 2016). Most of the charcoal (>70%) consumed in Zanzibar comes from mainland Tanzania, and more than half of the charcoal is traded illegally (Mwampamba 2007). About 3 million tons (3.6 million m^3) of wood are needed to produce the 28,759 bags (each weighing 56 kgs) consumed daily in Dar es Salaam alone (Malimbwi et al. 2005, 2007). The World Bank consultancy report of 2009 indicates that Tanzania consumed about 2650 metric tons a day, totaling to about 1 million tons of charcoal per year (WB 2009). Although charcoal is considered as a transitional energy to the more clean energy, research results show that it is still the main source of cooking energy consumed by the majority of people in towns, including the wealthier families. This is because of its reliability, availability, and easiness to trade and transport (Nyamoga et al. 2016).

The positive impacts of the growing demand for charcoal are the increased opportunities for income generation for both rural and urban population, through production and trading, thereby contributing to poverty alleviation (Zulu and Richardson 2013). In urban areas where woodfuel is scarce and alternative energy sources expensive, charcoal has enhanced the expansion of domestic markets and provided opportunities for households' savings. However, it also poses some challenges for sustainable production, environmental degradation, and negative health impacts on resource-poor households. Generally, charcoal economy and business encompasses numerous enterprises that support livelihoods in urban and rural areas (Boberg 1993; Van Beukering et al. 2007). Although lower-income households consume more charcoal per capita at relatively higher price per unit quantity (because of buying in small quantities), the wealthier households also consume substantial amounts of charcoal (Zulu and Richardson 2013). The high demand and consumption of charcoal makes it a potential income-generating activity along the value chain in both rural and urban areas.

Market and Marketing Systems in Tanzania

Several actors and institutions are involved in the charcoal value chain (Van Beukering et al. 2007); and in Tanzania about 2 million people are estimated to be involved in the entire value chain of charcoal (WB 2009). Most of the traded charcoal in Tanzania is produced locally and traded illegally through informal channels (Milledge and Elibariki 2005; Milledge et al. 2007). The informal charcoal trading channels tend to benefit producers, traders, and transporters but cause significant loss of government revenues through tax evasion (Milledge and Kaale 2005; Milledge et al. 2007; Sander et al. 2013). Formalizing charcoal trade is therefore essential to ensure that the necessary government revenues are collected efficiently (Schure et al. 2013). The formalization of charcoal trading is also necessary and advantageous for the government to have a record of all main agents in the charcoal value chain. Under the current system, charcoal is traded under informal conditions, characterized by dispersed, poorly developed, and weakly regulated markets (Zulu and Richardson 2013). Under informal systems, the key primary actors in the charcoal value chain such as producers, wholesalers, retailers, and transporters may be poorly coordinated and inefficient (Van Beukering et al. 2007). The World Bank (2009) reported that the value of the charcoal business in Tanzania was about USD 650 million, which was higher than the combined incomes from cotton, coffee, and tea in that year (WB 2009).

Charcoal Transport and Market Prices

Both commercial and noncommercial traders are involved in charcoal transportation using trucks, motorcycles, and bicycles and sometimes carrying on heads and shoulders (Malimbwi et al. 2007). Although the sector employs about 2 million people along the value chain (WB 2009), large profits are concentrated in the hands of wholesalers and transport agents, leaving the other agents more deprived (Van Beukering et al. 2007). Historical data show that the price of charcoal has been rising each year since 2000, and in 2004–2007 the market price of charcoal increased by about 160%, while the retail price increased by about 400% from Tanzania shillings 5000–25,000/= (per bag?) between 2003 and 2008 (WB 2009). The price increases are significant and provide incentives for producers and other stakeholders to engage in charcoal production and trading. As distance from the production center to the market increases, the prices per bag of charcoal at those production centers decreases (Hofstad and Sankhayan 1999). According to Hofstad and Sankhayan (1999), transport cost is an important component for deciding the price of charcoal in the urban markets. Since charcoal trading is mainly under the informal sector, there is minimal or no control by the government; hence no guidelines exist on wholesale and retail prices. Wholesalers and retailers tend to set prices based on the purchasing prices, transport, and other indirect costs incurred. The charcoal traders interviewed explained that the price of charcoal in the market sometimes depends on the tree species used and where the charcoal was produced, both of which are linked to the quality of charcoal. Currently motorcycles and bicycles are the major modes of transport for charcoal, especially in peri-urban centers thereby making it hard for the government officials to control.

Illegal logging and tree cutting for charcoal production are common in Tanzania, although very few published studies exist which have quantified these activities. However, reports from the Traffic revealed an illegal timber harvesting of about

30–70% in the Miombo woodlands (Milledge and Elibariki 2005; Milledge and Kaale 2005; Milledge et al. 2007). This amount is rather high and if excluded from regional or national analysis may mislead the conclusions and policy recommendations.

4 Conclusions and Future Research

The main objectives of this study were to give an overview of previous studies of charcoal production and consumption in Tanzania and to identify where improved information and research are mostly needed.

Tanzania's high population, urbanization, and economic growth influence strongly the country's consumption of charcoal. Since alternative energy sources are rather expensive, most urban households are expected to continue using charcoal as the main source of energy for cooking. Likewise, lack of affordable alternatives will force rural households to continue using firewood for cooking and heating. Producers will continue to engage in charcoal business as long as it is profitable, irrespective of the rates of deforestation.

This review shows that many interesting and valuable studies have been done about charcoal production and consumption in Tanzania. It is clearly seen how important these two topics are in social, ecological, and economic perspectives. However, many of the reviewed studies lack clearly specified hypotheses and specifications of behavior theories to be used for developing realistic and testable hypotheses. This should be improved in future research, because agent behavior assumptions are important for getting useful results in studies of charcoal consumers and producers. More studies are needed on factors effecting charcoal demand, like changes in prices, income, and policies. Using national household surveys like in D'Agostino et al. (2015) seems promising, but price and quantities of charcoal should be included as variables.

Regarding supply, more information is needed about regeneration (time and volumes) in miombo woodland for various tree species and locations. How various forms of land ownerships influence miombo woodlands management is another area where additional and improved information is needed. We also know very little about the possibilities and preferability in Tanzania of establishing forest plantations for producing charcoal – which species are suitable, which land is available, and what the costs would be.

Both charcoal demand and supply depend on policies – they make the frame within which supply and demand agents operate. Many policies are proposed in the reviewed studies, but little is known about their total and distributional impacts. More knowledge on this matter would be very interesting for policy makers.

Very few studies have been done in Tanzania about GHG impacts of charcoal production and consumption. These impacts might be high and rather decisive for the future land use in Tanzania, and more research on these matters should be implemented. Another interesting research area is the health impacts of using charcoal in urban households.

Charcoal production and consumption in Tanzania are linked to many urgent challenges – like land use, employment, income, global climate change, human health, energy security, and water availability just to mention a few. Many charcoal supply and demand factors interact, and it would be very useful to develop bio-economic models which include at least parts of these interactions and make possible consistent analyses of ex ante defined interesting changes from the present situation. This is a challenging but very interesting research task.

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Paper III

Econometric Analysis of Urban Household Charcoal Consumption in Tanzania

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ABSTRACT

Charcoal is the dominant source of cooking energy in Tanzania, with more than 80% of the urban and peri-urban population depending on it as their main source of energy for cooking. The urban population is currently increasing at an annual rate of 5-6 %, and it is important to get more reliable data on factors influencing the urban demand of charcoal in order to avoid severe deforestation and forest degradation. We present results from a survey of 360 households situated in the Tanzanian cities Dodoma, Morogoro and Mtwara about the impacts of income, charcoal prices and household size on the household per capita charcoal consumption. For the total sample, statistically significant elasticities for charcoal per capita consumption were found to be 0.03, -0.13 and -0.62 for respectively per capita income, charcoal price and household size. In the low income group, statistically significant elasticities for annual charcoal per capita demand were found to be -0.44 and -0.59 for respectively charcoal price and household size; in the middle income group only household size was found to be statistically significant with estimated elasticity -0.81; and in the high income group elasticities of 0.17 for per capita income and -0.44 for household size were found statistically significant. These results are based on small samples and should be viewed as exploratory results of value primarily as information for larger surveys.

Key words: *Urbanization*; *Elasticity; Efficiency; Charcoal Demand; Deforestation*

1 INTRODUCTION

Tanzania is experiencing population growth of about 2.7% per annum and an urbanization rate of 5 - 6% per annum leading to a significant expansion of urban and peri-urban settlements (NBS, 2017). More than 90% of Tanzania's energy consumption comes from forest sources largely in the form of charcoal or firewood (Mwampamba, 2007; Felix and Gheewala, 2011; Schure *et al*., 2013; Lusambo, 2016). Charcoal is the dominant source of cooking energy in Tanzania, with more than 80% of the urban and peri-urban population depending on it as their main source of energy for cooking (Zahabu, 2010; Chidumayo and Gumbo, 2013). Currently less than 33% of the Tanzanian population is connected to electricity sources – 17 % in rural and 64 % in urban areas (URT, 2015, 2017a) - but because of high costs and regularity concerns few households uses solely electricity for cooking. Rapid urbanization and high economic growth coupled with inefficient charcoal production and consumption technologies lead to increased wood harvests for charcoal production, and may cause severe deforestation, forest degradation and environmental problems (Hofstad, 1997; Kammen and Lew, 2005; World Bank, 2009).

Tanzanian land-use dynamics are of concern for many national and global interests focused on biodiversity, forest sustainability and land-use climate mitigation. Problems related to deforestation and land degradation are exacerbated by charcoal production, overgrazing and animal overstocking, weak land ownership and regulations, and poor farming practices such as shifting cultivation, slash and burn and monoculture practices (Mbaga-Semgalawe and Folmer, 2000; Kajembe *et al*., 2005; Mary and Majule, 2009). Approximately 55% of the Tanzanian mainland is covered by forests and protective measures ranging from strong in forest reserves and national parks (Malimbwi and Zahabu, 2008; Tomppo *et al*., 2010; Malimbwi and Zahabu, 2014) to weak in other areas subjecting them to illegal harvesting (Mwampamba, 2007). Annual deforestation is currently about 3728 km^2, equivalent to 1.1 % of the total forest area in the country (Bahamondez *et al*., 2010; Malimbwi and Zahabu, 2014). Land use, land use change and forestry is important in the context of Tanzanian Greenhouse Gases (GHG) emissions and climate policy (URT, 2017b) and also because Tanzania is among the 12 richest biodiversity countries in the world, due to its diverse forest types (Myers *et al*., 2000). This forest diversity provides habitats for the largest number of mammals, second largest number of plants, third largest number of birds, fourth largest number of reptiles and fourth largest number of amphibians in Africa (Burgess *et al*., 2002; Burgess *et al*., 2007; Pettorelli *et al*., 2010).

Reviewing the literature on charcoal demand and supply in Tanzania, Nyamoga and Solberg (2019) found only five studies from Tanzania which could be classified as econometric or quantitative demand studies (Hosier and Kipondya, 1993; Hofstad, 1997; Mwampamba, 2007; D'Agostino *et al*., 2015; Schaafsma *et al*., 2012). D'Agostino *et al*. (2015), analysing panel data from two national household expenditure surveys of more than three thousands respondents conducted in Tanzania in 2008 and 2010, found that charcoal was the preferred fuel of choice for the vast majority of urban households in Tanzania, but that the socio-economic determinants of this choice were still poorly understood. The household income, measured as monthly non-energy expenditure, showed a strong positive effect on charcoal expenditure with a statistical significant expenditure elasticity of 0.4 meaning that a 1% increase in household income raises charcoal expenditure by 0.4%, thus being an inelastic, normal good. In a households survey of 2670 respondents in Dar es Salaam, Mbeya and Shinyanga, Hosier and Kipondya (1993) found that energy consumption did not differ by income, and that electricity and liquidified petroleum gas (LPG) behaved as normal goods while kerosene was an inferior good. Woodfuel in forms of charcoal and firewood behaved as a normal good in low income groups and as an inferior good in the high income group

Hofstad (1997) found that as long as the cost of charcoal for household energy stays below that of kerosene and other improved cooking energies, the price elasticity of charcoal demand will remain the most important demand side factor influencing the rate of deforestation, and that switching to other forms of energy and thus reducing charcoal consumption and controlling deforestation is only possible at high prices of charcoal relative to the price of other energy carriers. In a survey carried out in 2002 of 244 households in six Tanzanian cities, Mwampamba (2007) found that the per capita consumption of charcoal ranged between 3.12–6.01 sacks or bags per person per year, equivalent to 93.6–180.3 kg per person per year with no significant difference in charcoal consumption between the low and middle income groups. He also found that per capita charcoal consumption decreased with increasing household size, and about 80% of the urban population used charcoal for cooking.

All these studies emphasize the need for improved information about the main factors influencing urban charcoal demand. For doing economic partial equilibrium analysis of the future development of charcoal consumption, estimates of both price and income elasticities are of particular interest. This paper addresses this concern and has as main objectives to provide an empirical analysis of which main economic factors drive household charcoal consumption in three urban areas of Tanzania, focusing on estimating demand elasticities for charcoal price, income per capita and household size.

The paper continues with a methodological section describing theory, hypotheses, data collection and statistical methods applied in the study. Then the results are presented in chapter 3 and discussed in chapter 4. Main conclusions are drawn in chapter 5.

2 METHODOLOGY

2.1 Theory and hypotheses

Charcoal consumption depends on a diverse set of factors including household income, availability of alternative energy sources, price of charcoal and alternative energy sources. Prior studies conducted in Tanzania, Uganda, Zambia and Sudan support this assertion and indicate that per capita consumption in urban centers is much higher than in rural areas (Hofstad, 1997; Zein-Elabdin, 1997; Malimbwi *et al*., 2007; Mwampamba, 2007; Peter and Sander, 2009; Fisher *et al*., 2011; Chidumayo and Gumbo, 2013; Lusambo 2016).

Rational choice theory assumes that choices are made individually or collectively based on the highest expected utility or return (Arts, 2012). Individuals tend to choose the best option from a range of alternative choices available (Zafirovski, 2003), although the rationale of such choices may be different when made at the individual compared to the collective level. In this study, we consider charcoal consumers as rational decision makers. We assume that the theoretical behavior model underlying the study is based on economic theory of household demand as described e.g. in Becker and Becker (2009) – i.e. a household allocates its income on expenditures (food, housing, energy, travels, school fees etc.) to get as high utility (or welfare) as possible given the constraints set by the household income and the prices of goods and services. Formally, we assume that a household maximizes yearly welfare of purchased goods and services, conditional on household income I and prices for various energy sources (p_1 for charcoal, p_2 for gas, p_3 for electricity) and other commodities and services (p_o). This gives the following short-term demand function for charcoal in household i (see e.g. Varian (1996, 2014):

$$d_i = d_i\,(p_1, p_2, p_3, p_o, I)$$

According to economic theory the hypothesis is that d_i decreases with increasing p_1 and increases with increasing p_2 and p_3, all other factors assumed equal. The impact of increased I is less certain, but here we used the energy ladder theory, which posits that households will shift to more advanced and clean energy types as income increases (Hiemstra-Van der Horst and Hovorka, 2008). Thus, our hypothesis regarding income is that per capita charcoal consumption decreases with increasing per capita income, all other factors equal.

2.2 Data Collection

Many charcoal studies have already been conducted in Dar es Salaam (Hosier and Kipondya, 1993; Hofstad, 1997; Sanga and Jannuzzi, 2005; Malimbwi *et al*., 2007; Malimbwi and Zahabu, 2008; Msuya *et al*., 2011, Faraji *et al*., 2015), and it was therefore decided to select the three urban regions of Dodoma, Morogoro and Mtwara as study areas. They were selected also because they are located as shown in Figure 1 in different climatic zones and in varying directions from Dar es Salaam, which is the main charcoal market and business center in Tanzania. Dodoma is the capital of Tanzania and currently houses among others the Parliament, all ministerial offices and two new universities, all of which have contributed in changing the socio-economic conditions of the region. Morogoro and Mtwara are located within the miombo woodland area where charcoal production is highly prominent. Mtwara, has seen economic expansions in recent years due to discovery and exploration of natural gas as well as a huge investment in cement production and establishment of new colleges and a university.

Socio-economic and charcoal consumption surveys were conducted during the period June-September 2015 in each of the three urban centers, and 120 households from each center were interviewed. The households were selected to represent respondents from low-income, middle-income and high-income categories. Among other questions in the survey, we asked about the price of charcoal per given unit (bag, sack or tin), amount of charcoal consumed per month, week or day, total annual or monthly income and the size of the household. The questionnaire we used in the survey is shown in Appendix 1.

The selection of respondents were done in two stages. First, in each of the three urban areas, the population was divided into different income levels by classifying the city wards and streets into three groups reflecting respectively the low, middle and high income households. The identification and classification of the wards on different social status was done in close collaboration with local government officials in order to capture the actual income differences in the cities. The households in the selected wards and hamlets were then assigned numbers and later drawn randomly in each street using the population registry in the local leaders' offices, in order to get sufficient number of respondents in each income class. Based on the income reported in the interviews the households were categorized into the following three income classes: (i) Low income – consisting of households with income less than Tshs 3,000,000 per annum, (ii) Medium income – comprising households with an income between Tshs 3,000,000 and 10,000,000 per annum and (iii) High income – containing households with income greater than Tshs 10,000,000 per annum.

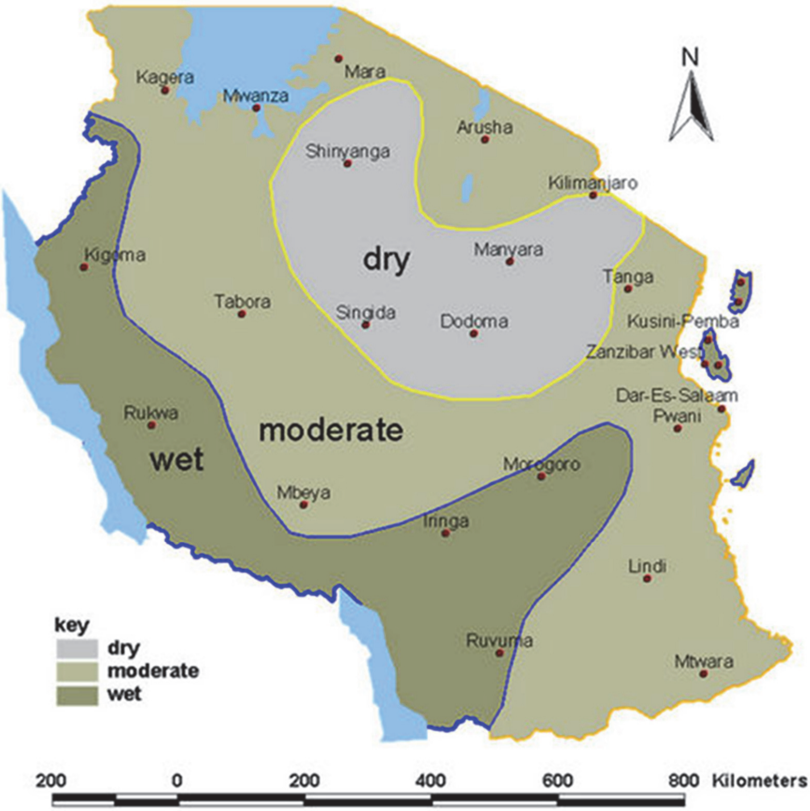

Figure 1: The location of Mtwara, Morogoro, Dodoma and other cities in Tanzania in relation to main climate zones. **Source**: (Ndomba 2013)

If possible, the head of households was interviewed, but in his or her absence, we interviewed any available member in the household who was above 18 years, knowledgeable and familiar with the required household data on income, household composition, economic activities and the daily or monthly consumption of charcoal and other types of energy consumed in the household. Our field data shows that most of the respondents were females, probably because they spend more time at home engaged in domestic work than their husbands. In case the interviewee felt he did not get sufficiently good information about the household expenditures, he communicated with the head of the household through phone call in order to acquire as reliable data as practically possible. During interviews it was observed that many households in particular in the low and middle income group, buy charcoal in smaller units than bags, depending on their immediate needs and financial situation. We recorded the units as presented by the interviewee and then converted the reported consumption into standard unit "normal bags", assuming 50 kg per "normal bag". Some households reported personal and business consumption of charcoal, but we excluded these commercial usages, so in the analysis only charcoal consumed at household level was included.

The total urban population of Dodoma, Mtwara and Morogoro is about 800 000 and represents about 15% of the urban population in Tanzania not including Dar es Salaam, and about 10% if Dar es Salaam is included (World Bank, 2015). Our sample is therefore rather small.

2.3 Statistical specifications

The original data set were first checked for outliers by performing influence measures tests, and altogether 27 of the observations were removed because of missing values and abnormalities. The statistical analyses were thus done using 333 households in the whole sample, of which 71 (21%) were high-income households, 142 (43%) were middle-income households and 120 (36%) were low-income households.

As household charcoal consumption is likely to increase with the number of household members, possibly introducing heteroscedasticity in the econometric estimation, we used per capita charcoal consumption as the dependent variable and, correspondingly, income per household member as independent variable. We also included number of household members as independent variable that reflects possible economies of scale in the cooking. Prices of alternative energy sources (electricity or gas) were excluded because very few of the respondents reported their use for cooking. Dummy variables for regions were tried, and also using no transformation of the data, but both alternatives were omitted because of reasons given in chapter 3.

The final econometric equation thus became:

$$\log C = a + b_1 \log P + b_2 \log I + b_3 \log H + \varepsilon \qquad \text{(Eq. 1)}$$

where:

- C is per capita consumption of charcoal (kg per capita per year)
- P is price of charcoal (Tshs per kg)
- I is annual per capita income (Tshs per year per person)
- H is number of persons per household
- a, b_1, b_2, b_3, are coefficients to be estimated and,
- ε is the error term

The data were analyzed using R program, version 3.2.5 - 2016-04-14 (Crawley, 2013). To check for heteroscedasticity Breusch Pagan Test (lmtest and NCV test) in R were used.

3 RESULTS

3.1 Description of sample characteristics and Tukey tests

In Table 1 mean values and standard deviations for consumption, income and household size are shown for the all observations and the three income groups. Boxplots of the observations are provided in appendix 2. Per capita charcoal consumption varies from 32 kg to 384kg (Figure A1 in Appendix 2), being on average lowest in the high income group and highest in medium income group (Table 1). Households are on average largest in the high income group and the total sample mean is 5.31 (Table 1) compared to the 4.5 obtained by the World Bank (2009) for Tanzania. The price of charcoal varies considerably between the three regions, with the average price in Morogoro being about double of the Mtwara price (Appendix 2, Figure A3).

Table 1: Descriptive statistics of the transformed and untransformed variables in the models for all observations and the three income groups (C, P, I, and H as defined in Eq. 1)

			Consumption C	Income I	Price P	Household Size H
Transformed (Log-Log)	Mean	All	4.83	13.72	6.14	1.58
		Low Income	4.82	12.53	6.17	1.53
		Medium Income	4.85	13.96	6.04	1.56
		High Income	4.80	15.24	6.29	1.70
	SD	All	0.51	1.18	0.37	0.44
		Low Income	0.52	0.69	0.36	0.45
		Medium Income	0.53	0.94	0.36	0.45
		High Income	0.45	0.61	0.37	0.35
Untransformed	Mean	All	141.90	1,766,337	496.79	5.31
		Low Income	141.92	346,735	510.14	5.07
		Medium Income	146.05	1,349,851	446.17	5.28
		High Income	133.58	4,998,634	575.48	5.77
	SD	All	72.50	2,338,354	198.11	2.23
		Low Income	74.97	257,798	193.63	2.21
		Medium Income	76.24	841,334	175.32	2.39
		High Income	59.65	3,160,864	220.69	1.85

Testing the group means using Tukey multiple pairwise-comparisons HSD (Tukey, 1949)- gave significant differences at 0.05 probability level for per capita income in different regions, per capita income in different income groups and price of charcoal in different regions and income levels. However, the per capita consumption of charcoal was not significantly different between income groups and regions, except for per capita charcoal consumption between Morogoro and Dodoma. Correlation coefficients for all variables were below 0.19, indicating low multicollinearity.

The fitted residual plots and the Q-Q plots behaves normally, and none of the estimated econometric equations violate the statistical assumptions of independence, normality and constant variance. The regression models were tested for heteroscedasticity using the Breusch-Pagan tests, both lmtest and NCV test (Breusch and Pagan, 1979), and the results indicating low heteroscedasticity.

3.2 Regression analysis results

For the whole sample, all three variables are significant, with elasticities being -0.13 for price and 0.034 for per-capita income (Table 2). The negative coefficient of -0.621for the household size implies economies of scale.

Dividing the respondents into three income level groups, per-capita income is significant only for the high-income group, with an elasticity of 0.17. Price is significant only in the low-income group, with elasticity of -0.44. Household size is significant in all three subsamples; with elasticities of -0.59, -0.81 and -0.44 in respectively the low, medium and high income group. The adjusted R^2 varies from 0.22 in the high-income group to 0.41 in the low-income group.

Table 2: Regression results of full sample and three income level samples

	Full sample (n=333)		Low income (n=120)		Middle income (n=142)		High income (n=71)	
	Coefficients	SE	Coefficients	SE	Coefficients	SE	Coefficients	SE
Intercept	6.138***	0.472	7.689***	1.075	8.490***	1.891	2.628	1.583
Per capita income	0.034*	0.020	0.061	0.066	-0.159	0.108	0.167*	0.094
Price of charcoal	-0.130**	0.063	-0.442***	0.102	-0.024	0.108	0.057	0.135
Household Size	-0.621***	0.055	-0.590***	0.082	-0.814***	0.081	-0.440**	0.160
Adjusted R^2	0.3162		0.414		0.3279		0.2195	
F-value	52.17		29.12		23.92		7.564	

'***' significant at level α = 0.01, '**' significant at level α = at 0.05 '*' significant at level α = 0.10

We also tried other statistical models, like total household consumption as dependent variable and charcoal price, total household income and household size as independent variables, or to exclude household size, or use no transformation of the input data. These specifications all gave lower R^2 and lower F-values or positive coefficient of charcoal price. Including region as explanatory variable, the price coefficient turned insignificant, probably due to the large differences in price levels between the three regions (Figure A3 in Appendix 2). We therefore rejected these models.

4. DISCUSSION

The higher prices of charcoal experienced in Morogoro and Dodoma than in Mtwara may be attributed by both demand and supply factors. The presence of the universities and other institutions in Morogoro and Dodoma contribute to increased population and purchasing power implying high charcoal demand. On the supply side, the Dodoma region experiences aridness most of the time as compared to Morogoro and Mtwara (Figure 1) and the increased demand has caused exhaustion of the woodlands and forests for charcoal production in Dodoma hence lowering the supply of charcoal from local areas. In Mtwara, the charcoal price can be explained by the high supply from the miombo woodlands in the region and low labour costs for charcoal production due to lack of work opportunities. Also, the distance from the production centers to the main markets implies lower charcoal prices in Mtwara compared to Dodoma and Morogoro. Previous studies have shown that Mtwara, Lindi and the neighboring regions are the main suppliers of charcoal to Dar es Salaam and Zanzibar (Malimbwi *et al*., 2007; Mwampamba 2007). Other studies have reported the highest price of charcoal to be in Zanzibar and Dar es Salaam, and that transport distances and costs are important factors for the market prices (Hofstad, 1997; Hofstad and Sankhayan, 1999; Mwampamba 2007). In addition, Malimbwi *et al.* (2007) found that of the 10,500 bags of charcoal transported daily to Zanzibar, about 7,500 bags (i.e. 72%) are transported illegally hence not charged with any taxations or levies, making charcoal available in the market at cheaper prices than if legally handled. The illegal charcoal production and trading system distort the market price of charcoal, and at the same time makes the government losing a substantial amount of revenues.

The main aim of this study was to provide usable estimates of charcoal demand elasticities. Regarding the charcoal price demand elasticity, the whole sample gave a statistically significant estimate of -0.13 which is in the same order of magnitude as earlier analyses mentioned in Nyamoga and Solberg (2019), although they were made many years earlier and under other energy prices.

The charcoal price demand elasticity estimated for the low income group is significantly higher (in absolute term) than for the whole sample. This result is in line with other Tanzanian studies e.g. (Hosier and Kipondya, 1993; Hosier *et al*., 1993; Zein-Elabdin, 1997; Sanga and Jannuzzi, 2005; Peter and Sander, 2009) which report that the high initial costs required tend to limit the low-income households to invest in electric, gas and improved charcoal cooking stoves.

In our study, charcoal price is not statistically significant in the middle and high income households. One possible explanation is that the poor families are living on a very strict household budget and are highly sensitive to changing charcoal prices compared with the richer families. In addition the poor urban families compared to the richer ones, may live in housing facilities which have more possibilities of using cheaper cooking energy substitutes like firewood or forest residues. For the richer households increased charcoal prices within the range observed in this study, might still result in charcoal being both cheaper and more reliable than shifting to electricity or kerosene cooking. Food tradition and taste considerations may also work for charcoal cooking in those groups.

For the entire sample the regression analysis resulted in a small, but positive per capita income elasticity of 0.03 statistically significant at 10% level. In the three stratified income samples, the per capita charcoal consumption variable was found statistically significant only in the high income group with elasticity 0.17. One should be very careful in drawing implications from these results, in particular those from separated income groups as the income variations within these groups are considerably smaller than for the whole sample. Nevertheless, it is noteworthy that the only statistical significant variables we found were positive, as it may indicate that the transition of going from charcoal to more modern cooking facilities like kerosene and electricity might take longer time than expected. Mwampamba (2007) and Hosier and Kipondya (1993) also found that income did not have significant effects on charcoal consumption in the households they investigated.

In chapter 1 we used the energy ladder theory to hypothesize that per capita charcoal consumption would decrease with increased per capita income. Our results regarding income are not showing this, but it would be misleading to claim that they do not support this theory as we had in our survey only few respondents which used electricity or kerosene for cooking.

The study includes several uncertain elements which should be kept in mind when interpreting or using the results. The interview situations where data were collected varied, as in some households other persons than the head of the household were interviewed. The income was estimated by using the respondents' answers on expenditures, and savings were not included. The definitions of the cut-offs between the three income groups could also impact the results. The charcoal prices were estimated based on various types of bag sizes.

Existing studies or official statistics that we could compare our study samples with would be beneficial. Regarding income classes, the only study we have come across was World Bank (2015), where the Tanzanian population is divided into the four income categories extreme poor, poor, middle class, and the richest. The percentage of total population in each of those classes was estimated indirectly to be 10% for the extreme poor, 28% for the poor, 40% for the middle class and 22 % for the richest class. In our study we had only three income classes and the following % distribution in the whole sample (see section 2.2): 36% in the low-income, 43% in the middle income and 21% in the high income group. If we add the two poorest classes in World Bank (2015) into one poor class, we see that the income distribution in our study is not very far from the income distribution shown in the World Bank study.

Also, our mean values for the annual per capita charcoal consumption are within the range of estimates in previous studies reported in e.g. Nyamoga and Solberg (2019). Misspecification of the statistical regression models is another potential reason for uncertainty. However, the Breusch Pagan Test (lmtest and NCV test) did not reveal any misspecifications.

In sum, considering all the above mentioned uncertainty factors, the study results should be interpreted with care, and should be viewed as exploratory and of value primarily as information for larger future household surveys in Tanzania. However, because so few studies of this kind have been conducted in the country, the results gives interesting results on the impacts of price, income and household size.

Improved studies of charcoal consumption in Tanzanian households are important and should compared to our study preferably be based on larger samples, include more regions and higher number of respondents including sufficient number of respondents who have moved from charcoal use to more "modern" cooking energy carriers. Detailed data on the consumption and costs of each of these carriers are important to include. More rigorous statistical tools than possible to apply in this study could then preferably be used, such as logit or Tobit models. To get enough number of respondents, one should try to coordinate with the existing Governmental household surveys done regularly in Tanzania.

With the current high rate of urbanization in Tanzania of about 5% per annum (NBS, 2017) and the high economic growth leading to increases in the middle-income population, growing demand of charcoal in the coming years seems very likely, causing increased environmental challenges like increased deforestation, reduced ecological resilience, increased GHG emissions as well as more urban air pollution. This will be the case if no alternative cooking energy sources will be available at affordable costs, especially for large and highly populated cities like Dar es Salaam, Mwanza, Mbeya, Tanga, Dodoma, Morogoro, Iringa and Arusha. The ongoing exploration of gas and the investment on the Stiegler's Gorge hydroelectric project in the country may contribute to changes of charcoal consumption patterns in these households in the future. But these changes will depend on many factors related to costs, consumer acceptance, technological changes, climate change policies and reliability of the new technologies. Studies about factors deciding changes from traditional cooking energy systems in Tanzania, represent a very interesting future research task. To avoid high negative impacts, many policy combinations like harvest regulations, more efficient charcoal production kilns, subsidies for electricity consumers, improved and more reliable electricity production, and clearer land ownerships have been proposed by several previous studies (e.g. Hosier *et al*., 1993; Hofstad, 1997; Sanga and Jannuzzi, 2005; Mwampamba, 2007; Schaafsma *et al*., 2012; World Bank, 2015). It is beyond the scope of this article to propose policy measures or to analyze their potential impacts. However, each choice of policies will have different economic, ecological and distributional effects, as well as ease of implementation. To arrive at good policy choices, it seems of high interest to develop and apply bio-economic models which can be used for analyses which include major economic, ecological and land-use interactions in a consistent way.

4 CONCLUSIONS

Charcoal is the main source of cooking energy in urban areas of Tanzania. We present results from a survey conducted in 2015 of 360 households from three urban areas in Tanzania to determine charcoal consumption's dependence of household income, charcoal price, and household size. For the total sample, statistically significant elasticities for charcoal per capita consumption were found to be 0.03, -0.13 and -0.62 for per capita income, charcoal price and household size, respectively. In the low income group statistical significant elasticities for annual charcoal per capita demand were found to be -0.44 and -0.59 for charcoal price and household size, respectively. In the middle income group, only household size was found significant with coefficient of -0.81 while in the high income group elasticities of 0.17 for per capita income and -0.44 for household size were found significant. The estimated charcoal price elasticity of -0.44 in the low income group indicates that the poor families are living on a very strict household budget and are highly sensitive to changes in charcoal prices compared to the richer families.

The study results are based on small samples and should therefore be interpreted and used with caution. Larger studies of charcoal consumption in Tanzanian households than this study are highly needed, and should preferably be based on larger samples, include more regions and higher number of respondents who have moved from charcoal use to modern cooking energy carriers, and include accurate data on the consumption and costs of these carriers. To get enough number of respondents, we suggest to coordinate such studies with the existing governmental household surveys done regularly in Tanzania.

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6 APPENDICES

APPENDIX 1: Household Questionnaire for Assessing Charcoal Consumption in Dodoma, Morogoro and Mtwara Urban Centers

SECTION A. GENERAL INFORMATION

1. Name of interviewer……………………………… 2. Date of interview……………..…..
3. Street……………………4. Ward…………………. 5. Town/district/city…………………

6. Household category

Category	Tick [✓]
High income	
Middle income	
Low income	

SECTION B. SOCIO-ECONOMIC CHARACTERISTICS OF THE HOUSEHOLD

7. Age of respondent…………………8. Sex of respondent [✓] 1. Male [ ] 2. Female [ ]

9. Highest education of the respondent [✓]
    1. Primary education [ ] 2. Secondary education [ ] 3. Tertiary education [ ]
    4. Informal education [ ] 5. Others (specify)……………………………………

10. Highest education in the household [✓]
    1. Primary education [ ] 2. Secondary education [ ] 3. Tertiary education [ ]
    4. Informal education [ ] 5. Others (specify)……………………………………

11. Household head: [✓]
    1. Male headed [ ] 2. Female headed [ ]

12. Relation of respondent to household head [✓]
    1. Him/herself [ ] 2. Wife/Husband [ ] 3. Son [ ] 4. Daughter [ ] 5. Others (Specify)

13. Marital status of the household head
    1. Single [ ] 2. Married [ ] 3. Divorced [ ] 4. Widow/Widower [ ]
    5. Others (specify)…………………………………

14. Household size and Composition …………………..
    0 – 5 Years…….. 6 – 13 Years……. 14 – 30 Years……… 30 Years and above……......

15. Main occupation (s) for the head of household…………………………………………...
    ……………………………………………………………….……………………

16. Household monthly/daily income (TZS)……….………………………. …………

SECTION C. HOUSEHOLD CHARCOAL CONSUMPTION

17. Do you use charcoal in your household? [✓] 1. Yes [ ] 2. No [ ]

If the answer in 17 above is **NO** give reason(s) if **YES** continue with 18
    ....

18. What are the main use(s) of charcoal in the household?
    1. Cooking food for household [ ] 2. Boiling water for drinking [ ]
    3. For ironing [ ] 4. Others (specify)…………………………………………….

19. What type of cooking stove do you use in your household? **[✓]**
    1. Common cooking stove (jiko) [ ] 2. Improved charcoal stove (energy serving) [ ]
    3. Modern gas cooker [ ] 4. Electricity [ ] 5. Others (specify)……………

20. Quantity of charcoal purchased or used in the household

Unit of charcoal purchased at household	**Purchasing Frequency**	**Purchasing Price per Unit**	**Annual Quantity of Charcoal Used**	**Annual Expenditure on Charcoal**
Bag (Kg)				
Large tin (Debe) (Kg)				
Small tin (Kopo) (Kg)				
Others (specify)				

Key: Frequency = Daily, Weekly, Monthly, Others

21. Do you know the main source (s) or tree species of charcoal you are using? [✓]
1. Yes [ ] 2. No [ ]
If the answer in 21 above is YES mention them……………………………………………….

22. Quantity of tree species used

Tree species	Quantity Purchased or Used

23. Do you have any preference from a certain species/source? [✓]
1. Yes [ ] 2. No [ ]
If the answer in 23 above is YES give reasons and the name of the species you prefer……..…
…………………………………………………………………..………………………………
24. Does the supply of charcoal change overtime? 1. Yes [ ] 2. No [ ]

Change in Supply of Charcoal for the Past 10 Years			Give the **Reasons** for Increase or Decrease in Charcoal Supply Overtime
Increase	**Decrease**	**No change**	

25. Did the price of charcoal changes in the past ten years? 1. Yes [ ] 2. No [ ]

Change in price of charcoal for the past 10 years			Give Reasons	Price of Charcoal	
Increase	**Decrease**	**No change**		**2012**	**2015**

26. Does charcoal from different tree species or places fetch different prices?
1. Yes [ ] 2. No [ ]

27. Which one normally fetches the highest prices?……………………………………………
28. Comparing to other energy sources, is the price of charcoal low, high or the same?
………………………………………………………………..
....

29. What challenges are associated with charcoal use in your household?
……………………………………………………………………………………………………
……………………………………………………………………………………………………

SECTION D. OTHER TYPES OF ENERGY USED IN THE HOUSEHOLD

30. Do you use other sources of energy other than charcoal for household uses? [✓]
    1. Yes [ ] 2. No [ ]

If **Yes** why? ………………… ………………… ………………… …………………

31. Mention the other sources of energy, which you would have used in the absence of Charcoal.

………………… ………………… ………………… …………………

32. Other sources of energy used in the Household apart from charcoal?

Sources of Energy	Purchasing Frequency	Price per Unit	Annual Quantity Purchased
Firewood			
Gas			
Kerosene			
Electricity			
Others (specify)…			

Key: Frequency = Daily, Weekly, Monthly, Others

33. Do you have specific uses(s) for each type of energy source?
    1. Yes [ ] 2. No [ ]

34. What are the main use(s) for each type of energy source in the household?

Energy Source	Main Uses: 1. Cooking 2. Boiling water 3. Ironing 4. Others
Firewood	
Gas	
Kerosene	
Electricity	
Others	

35. Why do you have to use different energy sources for different activities?..........................
…………………………………………..…………………………………………………………

36. What challenges are associated with the use of other type of energy source(s) used in the household?..........……………………………………………...………………………
…………………………………………………………………………………………….

37. On average, what is the monthly total expenditure of your household for all the consumptions such as food, energy, transport, school fees and other social activities?...................................

THANKS FOR YOUR COOPERATION

APPENDIX 2: BOXPLOTS OF DATA

Figures **A1-A10** show box-plots of the samples in which the dark horizontal line shows the median value, the low and high line of the green box show respectively the value of the 25% and 75% sample quartiles, the two outer lines show the low and high sample value which are respectively plus/minus 1.5 standard deviations from the mean, and the dotted circles shows all sample values which are outside this range.

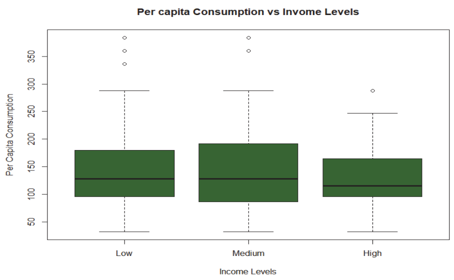


Figure A1: Box- plot of per capita charcoal consumption (y-axis in Kg/person per year in the three main income samples (x-axis in

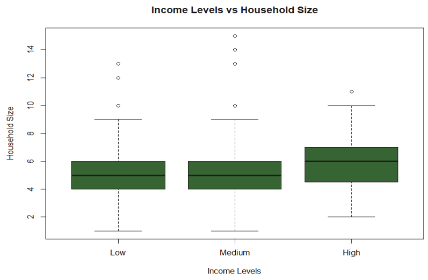


Figure A2: Box-plot of household size (y-axis) in the three income samples (x-axis)

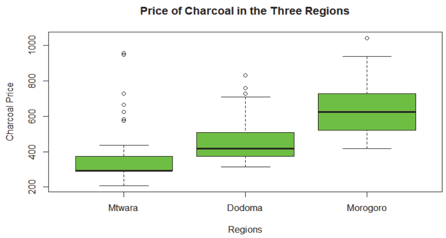


Figure A3: Box-plot of price of charcoal (y-axis in Tshs/Kg) in Dodoma, Morogoro and Mtwara (x-axis)

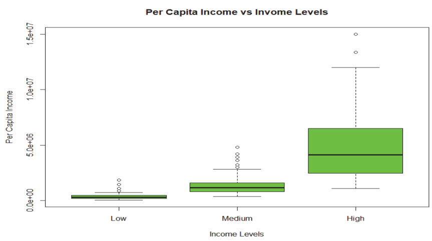


Figure A4: Box-plot of per capita income (y-Axis in Tshs) in Low, Medium and High income samples (x-axis)

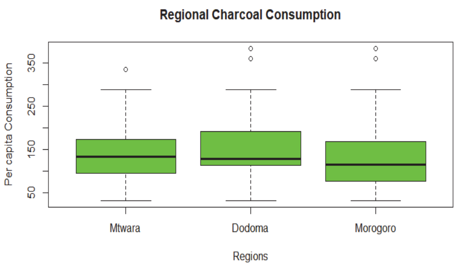


Figure A5: Box-plot of per capita charcoal consumption (y-axis in Kg) in Dodoma, Morogoro and Mtwara (x-axis)

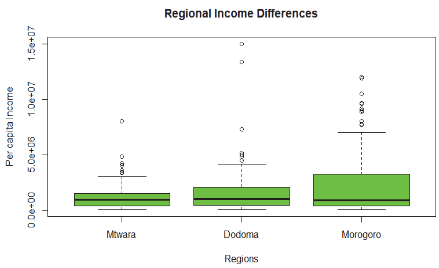


Figure A6: Box-plot of per-capita income (y-axis in Tshs.) in Dodoma, Morogoro and Mtwara (x-axis)

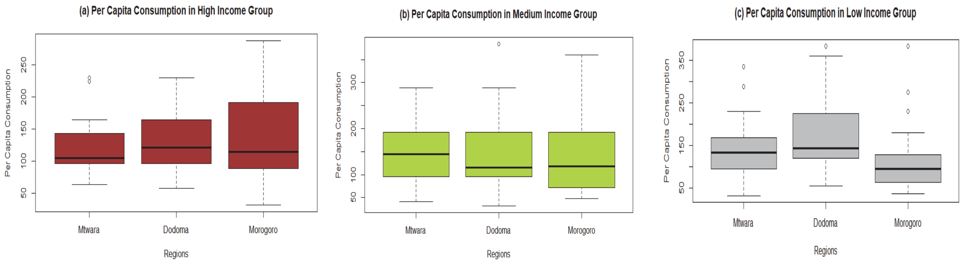


Figure A7: Per capita charcoal consumption (y-axis in Kg) in (a) High, (b) Medium and (c) Low Income Groups in the three Regions (x-axis)

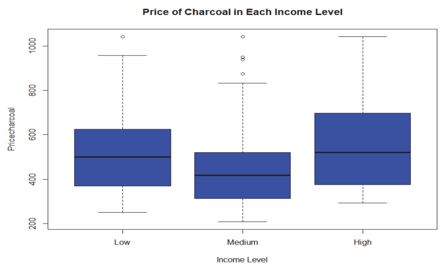


Figure A8: Comparison of price of charcoal in each Income Level

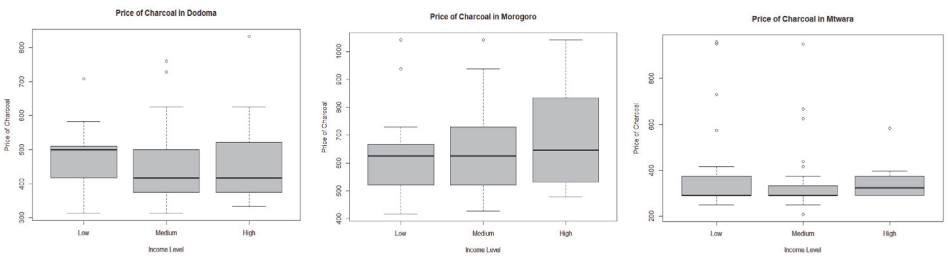


Figure A9: Price of Charcoal for each Income group in each Region

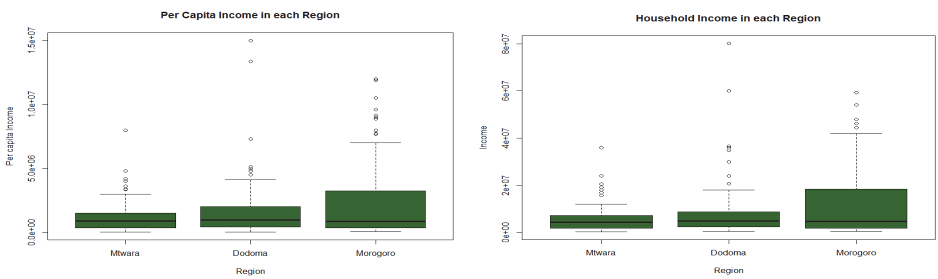
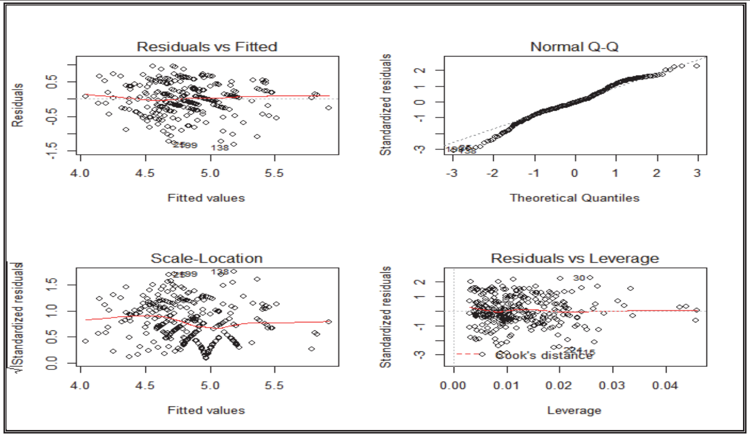
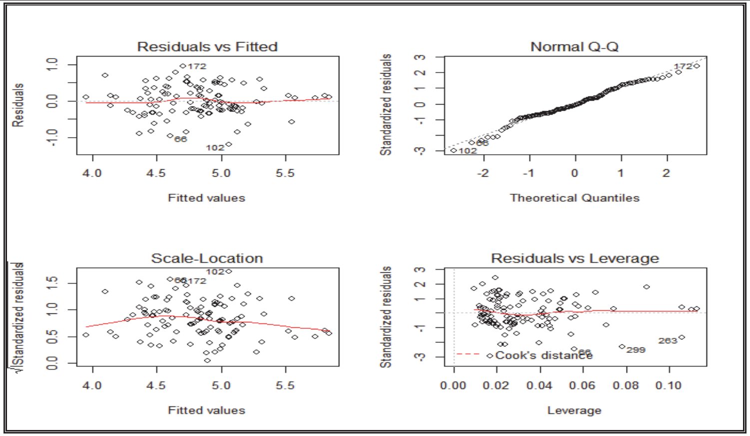


Figure A10: Income and Per Capita Income in each Region

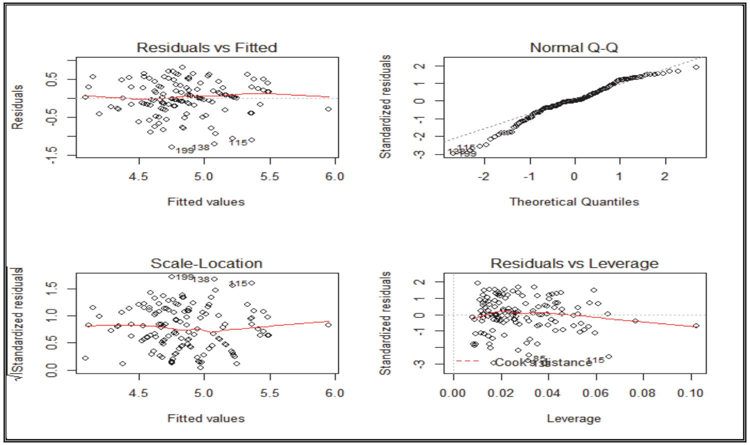
APPENDIX 3: RESIDUAL PLOTS FOR THE REGRESSION EQUATIONS SHOWN IN TABLES 2



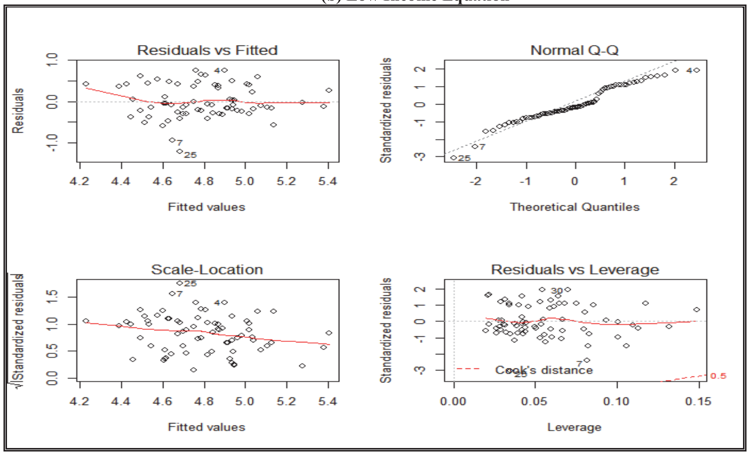
(a) Full Sample Equation



(b) Low Income Equation



(c) Middle Income Equation



(d) High Income Equation

Paper IV

Developing a dynamic partial equilibrium forest sector model for mainland Tanzania and assessing impacts of firewood and charcoal production and consumption on forest sustainability

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ABSTRACT

Forest degradation and land rehabilitation are major concerns in Tanzania. The wood harvested for charcoal, firewood and poles constitutes more than 90% of the country's estimated total forest harvest. The primary objectives of this study are to develop a forest sector model which integrates detailed forest data from 32,773 sample plots in Tanzania's National Forest Inventory (NFI) NAFORMA with data on demand for wood products, and apply the model to evaluate sustainability impacts of the future production and consumption of firewood, charcoal and poles. The developed model (TanzFor) is an intertemporal dynamic, spatial partial equilibrium model and links in an economic consistent framework supply and demand for fuelwood, poles and charcoal. The study is the first in Africa applying this type of a model with data from a detailed NFI and newly developed forest growth functions as basis for future wood supply. The first version of the model presented here includes many uncertain data inputs and assumptions. Nevertheless, the study shows alarming negative impacts on forest growing stocks by the steadily increasing consumption of firewood and charcoal in Tanzania, mainly caused by high population growth, high urbanization rates, low efficiencies in both charcoal production and consumption, and free access to common pool resource (CPR) land. Future promising research tasks include further use of the NAFORMA data, provision of more accurate data on the present and future consumption of charcoal and firewood, analyses of property regimes' effect on wood supply, improvement of TanzFor and its application in policy analysis related to land use and forest climate change mitigation and adaptation.

Key words: *Deforestation, land use changes, urbanization, population, efficiency, technological changes, NAFORMA, land degradation, REDD+, TanzFor*

1 INTRODUCTION

1.1 Background

Tanzania is endowed with a wide range of natural resources including forests, wildlife reserves, national parks, mountains, rivers and lakes providing ecological and cultural diversity. It's total area of about 947,600 km^2 is primarily composed of about 945,100 km^2 in mainland Tanzania while the remaining 2,500 km^2 consists of Unguja and Pemba Islands of the region of Zanzibar (Malimbwi and Zahabu, 2014). About 55% (48.1 million hectares) of the total area in mainland Tanzania is covered by forest dominated landscapes (Malimbwi and Zahabu, 2014). The predominate forest type is the Miombo woodlands that occupies lowland areas across the central and southern parts of the country while other forest types including the Acacia woodlands, the coastal forest/woodland mosaic, mangrove forests and the closed canopy forests are found on the ancient mountains of the Eastern Arc (ibid). Forest plantations are estimated to cover between 190,000 and 250,000 ha of which about 85,000 ha are industrial plantations managed by the government of Tanzania, and the remaining plantations consist of 40,000 ha owned by private companies and 80,000-140,000 ha owned by villages or individual households (Ngaga, 2011; Schaafsma *et al*., 2013; Schaafsma *et al*., 2014). Large uncertainties exist about the quantities of wood harvests in Tanzania; however, FAO (2018) gives the following official annual harvest volumes for Tanzania including Zanzibar for 2014 (all figures rounded off to the nearest thousand):

Firewood coniferous	32,000	m^3
Firewood non-coniferous	23,800,000	m^3
Sawlogs and veneer logs coniferous	674,000	m^3
Sawlogs and veneer logs non-coniferous	111,000	m^3
Pulpwood coniferous	172,000	m^3
Pulpwood non-coniferous	37,000	m^3
Other industrial roundwood	1,616,000	m^3
Charcoal made of wood	1,816,000	tonnes

The total industrial wood harvest sums up to 2.7 million m^3. Assuming 7.5 m^3 wood input per ton of charcoal produced (Monela *et al*., 2007; Malimbwi *et al*., 2007), the total wood harvest in 2014 was 40.2 million m^3. The quantity of wood harvested for charcoal and firewood combined would be 37.5 million m^3, thus constituting more than 93% of the above reported total harvest.

Tanzania's Gross Domestic Product (GDP) in 2015 is estimated to be Tshs. 12.4 trillion equivalent to 5.42 billion USD and growing at the rate of 6.8% p.a. (URT, 2017a). Agriculture, forests and hunting altogether comprised in 2016 about 31% of the GDP while the service sector (trade, transport, communication, hotel and restaurants) and the manufacturing sector (industry and construction) contributed 42% and 25 %, respectively. The contribution of forestry to the GDP is uncertain, but based on Abaza (2002) an estimate of about 3.5 % of GDP seems realistic around year 2000.

Deforestation, forest and land degradation are serious challenges in Tanzania, and studies indicate losses as high as 373,000 ha of forest each year (Tomppo *et al*., 2010; Tomppo *et al*., 2014; Nyamoga *et al*., 2016) due to various reasons, including clearing for agriculture, illegal logging, forest fires and charcoal production (URT, 2015a). While accurate estimates of past deforestation, forest growth, and forest growing stock levels have been difficult to get, the first round of the National Forestry Resource Monitoring and Assessment of Tanzania Mainland (NAFORMA) was completed in 2014 (URT, 2015a,b), giving Tanzania a national forest inventory (NFI) based on more than 32,000 permanent sample plots. This inventory, described more detailed in section 2.2, makes possible rather accurate estimates of forest growing stock and its distribution of tree species, vegetation and land use types as well as ownership categories. It also opens the possibility for a wide range of analyses evaluating the impacts of changes in harvesting and other forest management options. In particular, the NAFORMA makes it possible to integrate consistent estimates of forest growth and removals on the wood supply side, with manufacturing and demand for forest products, at both the regional and national level.

The single largest component of Tanzanian forest product demand is bioenergy with about 90% of energy needs in the country supplied from wood-based fuels (Malimbwi *et al*., 2007; Malimbwi and Zahabu, 2008; Sawe, 2012). This high dependency on wood-based energy makes charcoal and fuelwood the primary drivers of deforestation in the country. Studies show that to produce 1 ton of charcoal, 6.5-8.5 m^3 of wood is used today in Tanzania (Luoga *et al*. 2000a,b; Malimbwi *et al*., 2007; Monela *et al*., 2007; Msuya *et al*., 2011; Sawe, 2012; Nyamoga and Solberg, 2019). Most of the charcoal is consumed in urban areas, due to its relatively lower price and convenience in transporting, distributing and storing (Sawe, 2012). The population in mainland Tanzania in 2014 was estimated to be 54 million people and is growing at an annual rate of 2.7% (NBS, 2017a,b,c). The urban population in 2014 was comprised of 19 million people, i.e. 32 % of the total population, and was growing at a rate of 5.2 % per annum (WB, 2018; NBS, 2015a,b). The high population growth and urbanization rates result in increased consumption of wood products, in particular charcoal. This implies continued pressure on forest resources and land use.

Wise policy design and decision making requires good knowledge about the potential impacts of alternative choices. Many analyses have been published on forest sustainability and demand growth in Tanzania. Nyamoga and Solberg (2019) give an overview of recent studies related to charcoal and fuelwood. A recurring theme in this literature is the sustainability impacts of meeting the likely future demand of these products. However, nearly all of the studies have been local or regional in scope with a focus on either production or consumption. There have been, however, two studies where forest growth (as wood supply) and forest product consumption (as wood demand) in Tanzania have been analysed in an integrated way at national level. Ngaga (1998) applied a dynamic-recursive partial equilibrium forest sector model to evaluate supply and demand for forest industry products in Tanzania based on wood supply from softwood plantations only. Only forest industry productions (sawnwood, particleboard, fiberboard, and paper) were included and neither fuelwood nor charcoal were considered. The second study (World Bank, 2009) is a simulation analysis of forest degradation impacts of charcoal consumption in Dar es Salaam. This study uses a simple spreadsheet model with no dynamic forest growth or market aspects included to simulate how household demand and various policy means impact the utilization of forest resources. None of these two studies had the possibility of using a NFI as detailed as NAFORMA.

1.2 Objectives of the study

The primary objective of this study is to integrate the detailed NAFORMA forest data with demand for wood products in a dynamic forest sector model that can be applied to evaluate sustainability impacts of the future demand for charcoal, fuelwood and poles. Specifically, we want to: (i) develop and document a dynamic partial equilibrium forest sector model for mainland Tanzania, (ii) apply this model for assessing how much increased demand for charcoal, fuelwood and poles may impact harvest in miombo woodlands at regional and national levels in mainland Tanzania, and (iii) discuss major implications of the findings, with emphasize on future research priorities. Main efforts on this study are given to objectives (i) and (ii).

While the model developed and employed in this study includes forest industrial products and softwood plantations, this paper focuses on only fuelwood, charcoal and poles from miombo woodlands as these products are by far the most important ones for forest degradation in Tanzania and only to a very small degree come from softwood plantations.

The remaining part of the paper is organized as follows: In chapter 2 the model and data input are described. In chapter 3 the findings of the study are presented and in chapter 4 a discussion of key findings follows. Finally, main conclusions are drawn in chapter 5.

***Figure 1**: Map of Tanzania and regions of the country*

2 METHODOLOGY

2.1 Data

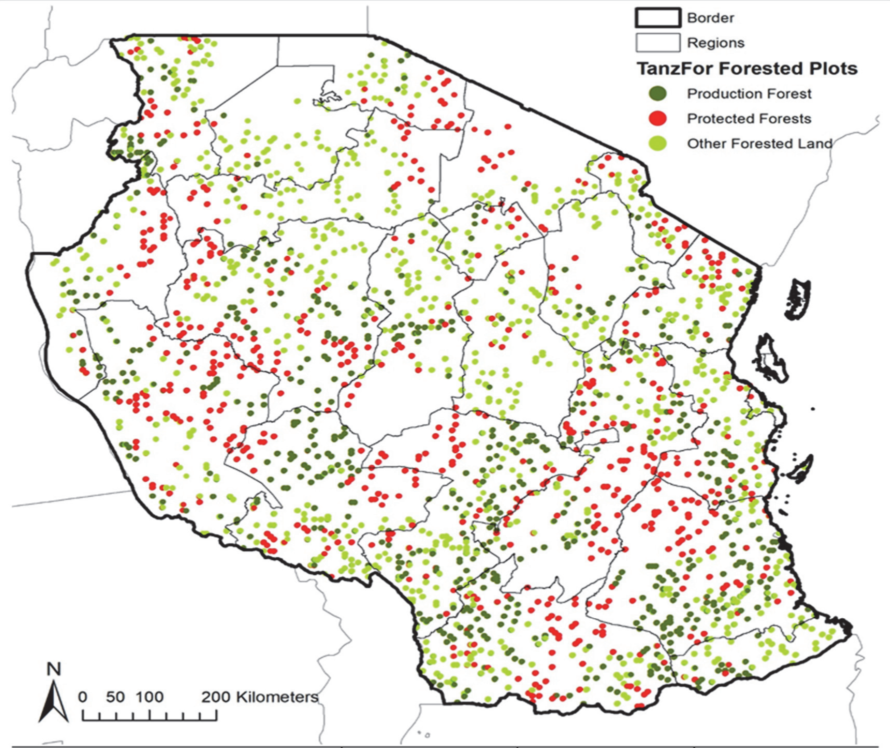
2.1.1 Forest data

This study covers the total forest area in all regions of mainland Tanzania (Figure 1) with the total forest area of 48.1 million ha covering about 55% of the total land area in the country. About 30% of the land in Tanzania is used for agriculture while 32.5% is protected forests or wildlife reserve areas (Malimbwi and Zahabu, 2014; Tomppo *et al.,* 2014). URT (2015a) reports the total growing stock (stem volume) in the country to be 3.3 billion m^3.

Table 1: *Domestic regions used in the model*

Region Number	Name of the Region
1	Dar es Salaam
2	Morogoro
3	Pwani
4	Lindi
5	Mtwara
6	Ruvuma
7	Rukwa
8	Njombe
9	Iringa
10	Mbeya
11	Manyara
12	Dodoma
13	Singida
14	Mara
15	Simiyu
16	Mwanza
17	Kagera
18	Geita
19	Tabora
20	Shinyanga
21	Kigoma
22	Katavi
23	Kilimanjaro
24	Arusha
25	Tanga

All initial forestry data is based on the data from the 32,773 sample plots of NAFORMA, which are clustered in 3,419 statistically representative grid structures as described in URT (2010) and URT (2015a). One fourth of the sample plots are permanent. The forest representation in TanzFor model is comprised of the individual tree and plot data from the 15,180 forested NAFORMA plots. The plot data are classified according to 28 vegetation types, 9 land use categories and 6 ownership classes. The model separates plantation wood from natural forest systems and restricts harvesting and gathering of wood from reserved forests. Figure 2 shows the distribution of the forested plots utilized by TanzFor model along with a general land use classification. It also highlights the broad land use classification by ownership. The largest ownership being villages and the central government covering over 29.7 million of the 42.8 million hectares of forests with 10.8 million hectares of the central government land (88%) being in protective status.



Forest Ownership	Production Forest		Protected Forest		Other Forest Land		Total Forest land	
	Plots	Hectares	Plots	Hectares	Plots	Hectares	Plots	Hectares
Central Government	352	1,007,682	3,535	10,871,204	146	457,825	**4,033**	**12,336,711**
Local Government	285	775,489	472	1,531,845	52	206,199	**809**	**2,513,534**
Village	3,540	9,063,787	1,098	3,010,279	1,863	5,333,531	**6,501**	**17,407,598**
Private	314	805,074	59	145,346	2,771	7,597,515	**3,144**	**8,547,935**
Other	546	1,556,448	31	84,626	116	360,449	**693**	**2,001,523**
Total	**5,037**	**13,208,480**	**5,195**	**15,643,300**	**4,948**	**13,955,520**	**15,180**	**42,807,301**

***Figure 2**: Distribution of forest plots in NAFORMA, Source:* URT 2015a

We assumed that fuelwood, poles and charcoal could be taken from all vegetation types except from the land types protected forests and forest reserves, wildlife reserves, and mangrove forests. Regarding plantations we allowed for poles and fuelwood extractions in *Eucalyptus* and *Acacia Mearnsii* plantations, and in *Acacia Mearnsii* plantations we allowed also for charcoal production. In each of the regions shown in Table 1 the NAFORMA sample plot data were used to find standing volumes for various species and vegetation types in the base year 2014. To simulate the future development of each of these plots, we used the growth, mortality, and recruitment functions in Mugasha *et al*. (2017). Stem and branch volumes are estimated using equations from Mauya *et al*. (2014) and biomass in above-and-below ground components using the functions in Mugasha *et al*. (2013). The growth projections begin in 2014 and were conducted over a total of twenty 5- years' periods thus allowing evaluation of harvest possibilities for a 100-year timeframe.

Harvesting options include a clear-felling or a partial harvest of either 20%, 12%, or 5% of the volume in trees with breast height diameter larger than 5 cm. Based on Chidumayo and Gumbo (2013) we assumed that the reentry period for partial harvesting on each plot would be every 10 years.

2.1.2 Data on production and consumption

Following NBS (2017a,b) the annual population growth was assumed to be 2.7% till 2030, then 2.3% till 2040, and thereafter 1.7% during the period 2040-2114. Regarding urbanization we have used as starting point the population for 2014 distributed on urban and rural areas as published in NBS (2015a,b) for each region of mainland Tanzania, and a future urbanization rate as shown in Appendix 2, also based on NBS (2015a,b). This results in the population development shown in Figure 3.

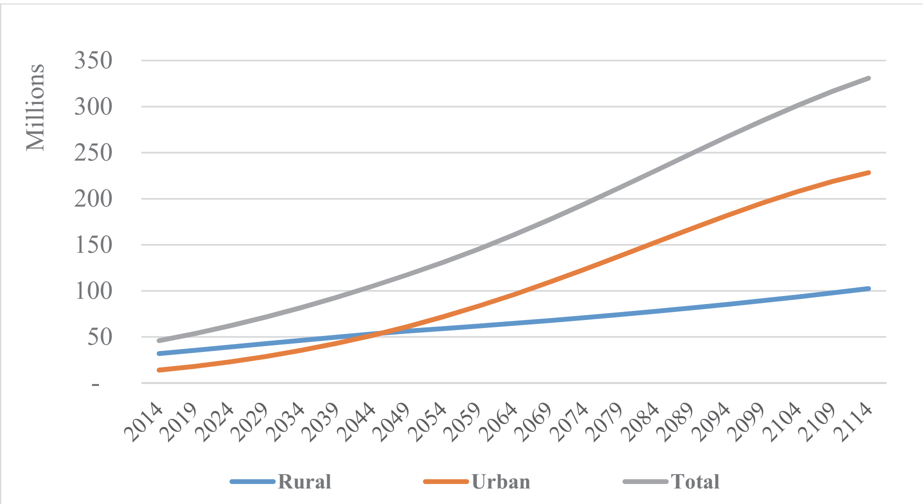


Figure 3: *Urban, rural and total population development in Tanzania mainland (million persons).* ***Source****: Estimated based on NBS (2017a,b,c)*

Appendix 2 also provides an overview of other data assumptions used in projecting consumption for the starting year 2014 and 100 years ahead through 2114. After the initial year 2014 we assumed three alternative scenarios regarding the development of future wood use, labelled respectively Low, Base and High scenario. This classification relates to the following assumed technological improvements over time in charcoal production (i.e. kiln efficiency estimated as m^3 wood biomass used per ton of charcoal produced) and charcoal consumption (i.e. household stove efficiency measured as kg charcoal used per capita):

- In Base ("Medium") alternative: 0.5% p.a.
- In High charcoal consumption alternative: 0.25% p.a.
- In Low charcoal consumption alternative: 1.0 % p.a.

In addition we operate in section 3.2 with an Extreme Low scenario as defined there.

2.2 Forest sector model description

For this study we create an intertemporally optimized spatial partial equilibrium model of the Tanzanian forest sector (TanzFor) in the terminology of Latta *et al*. (2013). It is an equilibrium model as it secures that supply of wood resources in each time period that equals demand for firewood, charcoal, wooden poles and forest industry products in each region, including the potential for trade between each region and optimizing over the whole time horizon. Thus, the harvest in each region depends upon the costs of production and transport as well as the regional willingness to pay for wood. TanzFor model includes 25 domestic regions (Table 1) to capture the regional differences in terms of vegetation types, forest growth potential, population growth, economic growth, urbanization as well as demand for forest products and interregional trade. In addition a foreign region is included in the model to allow for Tanzanian imports and exports in the balance of market and product movements. In this paper, we have assumed that the foreign trade of forest products are as specified in Appendix 3 Table A4.

Formally, TanzFor model can be characterized as a dynamic, spatial equilibrium model where the market clearing prices and quantities are found by maximizing the discounted sum of regional net social surpluses less transportation costs between regions. A mathematical description of the model laying out the piecewise integration of the objective function and nine constraints defining acreage allocation, harvesting, and market-clearing equilibrium is found in Appendix 1, where also the demand function is explained rather detailed. One difference from the Samuelson (1952) approach lies in the treatment of timber supply which is not driven by supply curves but rather through harvest scheduling combining the features of a Johnson and Scheurman (1977) model I and II formulation. Any part of a NAFORMA plot can either experience a partial harvest thus reducing forest stock, affecting ingrowth and altering the growth rate, or a regeneration harvest in which case the plot returns to age zero. Upon harvest the logs are allocated to a forest product incurring a product-specific manufacturing cost (Table A1 in Appendix 3) prior to being transported to a region to meet its demand. Fuelwood costs have been set to zero in rural areas as nearly all fuelwood is collected by the user. Transportation cost considerations are provided in Appendix 3.2. Demand for each product in each region is defined by a constant elasticity demand function set at the current price and quantity and shifted over time based on exogenously determined levels of population growth (distinguishing between rural and urban population growth in each region), economic growth for each region, and technological improvements as described in section 2.1.2 and Appendix 2. Based on Nyamoga and Solberg (2019), we used a price elasticity of -0.17 for retail charcoal prices. In urban areas we have assumed that the retail price per m^3 wood is half the corresponding charcoal price. Elasticities for other TanzFor products are given in Table A5 in Appendix 3.

The set of constraints control the land, and harvest allocation as well as ensuring balance in supply and demand are provided in Equations A6 - A14 of Appendix 1. The model time steps are 5-year periods and a real discount rate of 6% p.a. was used in the analyses. The non-linear specification laid out in Appendix 1 is solved for each scenario by linear programming using piecewise integration over a scenario-specific time period (up to 100 years).

3 RESULTS

A model such as TanzFor generates large quantities of interesting information, but because of space limitations in this article we have concentrated on three primary sets of results. When the model was run using the Base scenario demand for 100 years (2014 - 2114), harvest levels could not be maintained past 2059. Based on this we decided to apply the model in three different sets of analyses, giving three sets of results. The first set focuses on sustainability and how long-term demand can be met when using (i) only the forest areas designed today for harvesting, and (ii) also using today's forest reserves – i.e. forest areas not allowed to be cut. This set of results shows the pressure which the Base scenario would bring on utilizing restricted forest land.

The second set of analysis isolates the demand component of the model for charcoal, fuelwood and poles in the three technological scenarios Base, Low and High defined in section 2.1.2 assuming no wood supply constraints – i.e. only the wood demand assumptions based on growth in urban and rural population in each region and the technological improvements defined in section 2.1.2 are taken into account. No costs and prices or economic equilibrium estimates are considered, and we evaluate the level of technological improvements necessary in charcoal production and consumption to counteract future demand increases.

The third set of analysis again uses the full model yet concentrates on the period 2014-2059 and analyses the impacts of each of the three scenarios Base, Low and High defined in section 2.1.2. In addition to the harvest and inventory levels we explore the regional differences in price effects. All result charts report on the y-axis the annual roundwood volume (including branches) required to meet the demand.

3.1 Wood supply sustainability impacts of meeting the Base scenario demand in a 100 years perspective

Figure 4 shows the TanzFor model results for the Base scenario of 100-years of harvesting with and without maintaining the 15.6 million hectares of protected areas and reserves. In the left panel we see that when the protected areas and reserves are maintained, the harvestable inventory rises to year 2044, then falls dropping by over one half by the end of the 100-year time horizon. The right panel tells some more of the story as the harvest rises through 2059 and then hovers at approximately 150 million cubic meters per year before eventually falling precipitously in 2079 through the end of the modeling time horizon as the merchantable trees on harvestable lands are exhausted.

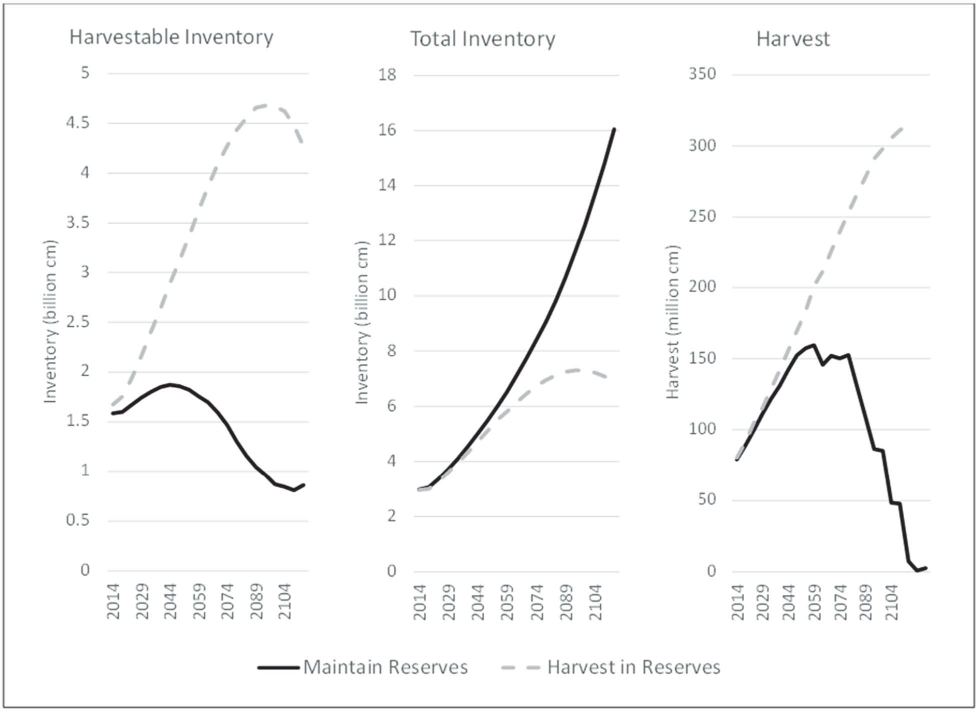


Figure 4: *Results of nationwide harvestable inventory, total inventory, and harvest levels with and without maintaining protected areas and reserves in mainland Tanzania*

The dashed lines in Figure 4 indicate what the situation would be if the pressure of not meeting demand over the next century leads to a breakdown of the protected area and reserves, and harvesting takes place across all forests of mainland Tanzania. In the left panel we see that the stocks on harvestable lands triple before beginning to fall in 2094. The middle panel shows that the inventory decline at the end of the century is consistent with that of the harvestable lands, and indicates that while utilizing all forest land of Tanzania avoids the midcentury collapse of harvest, adding in protected forests only adds another half century before all forests are in decline.

3.2 Consumption of charcoal, fuelwood and poles without wood supply constraints

From the results in Section 3.1 it is clear that the combined effects of population, technological improvements and urbanization in the Base scenario exceed the resource production of legally available forests. Figures 5 shows the development of the demand of wood for firewood, charcoal and poles in mainland Tanzania under the assumptions of population growth, per capita wood consumption and technological efficiencies in the production and consumption of charcoal specified in section 2.1.2 and assuming no wood supply constraints – i.e. that we just project the demand and does not consider that in practice demand has to equal supply. We clearly see that the pole quantities are very small compared to the energy components of total wood demand.

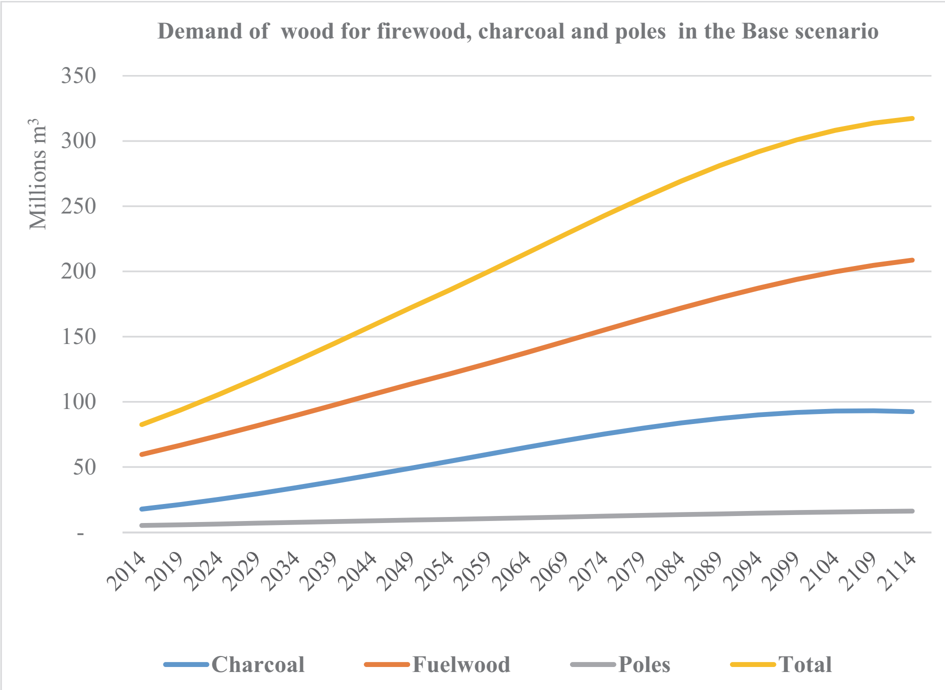


Figure 5: *Demand of wood for firewood, charcoal and poles in mainland Tanzania in the Base scenario assuming no wood supply constraints (million m^3 per year)*

Figure 6 isolates charcoal demand focusing in the left panel on the spatial distribution of charcoal consumption and in the right panel looking at how that demand evolves over time in the Base scenario both in Dar es Salaam and in the other regions combined. The map of current consumption highlights the concentration of demand in three primary locations (Dar es Salaam – 6.63 million m^3, the combined Mwanza– 0.94 million m^3, and Mbeya and Songwe[1] – 0.91 million m^3). The right panel of Figure 6 shows that the dominance of Dar es Salaam charcoal demand is projected to continue through 2114 moving from 44% of total charcoal demand down only 1% point as it increases 6 times over.

[1] Songwe was created in 2016 from the western half of Mbeya region. For the purposes of this analysis we treat them as a combined single region.

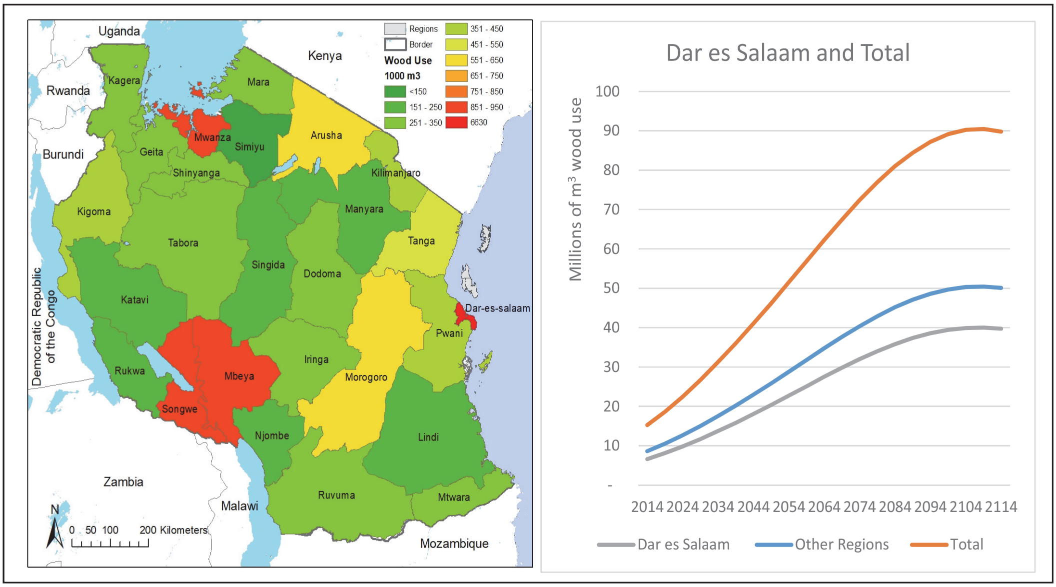


Figure 6: *Demand of wood for only charcoal production in mainland Tanzania distributed on regions in 2014 (left panel) and for the period 2014-2114 in the Base scenario (right panel) assuming no wood supply constraints (million m^3 per year)*

An interesting consideration is the degree to which technological investments in both the production and consumption of fuelwood (i.e. firewood and charcoal) and poles in mainland Tanzania could ease the pressure on the forest resource base. We systematically increased the technological improvement assumptions of section 2.1.2 until the combined urban and rural demanded volume remained below 100 million m^3 (again with no wood supply constraints). This stabilization of demand was achieved with a 2% annual technological improvement (otherwise same assumption as in the Low Charcoal Consumption Scenario defined in Appendix 2) and we label this special case scenario Extreme Low Scenario and present how it relates to the Base, Low and High scenarios in both rural and urban areas in Figure 7.

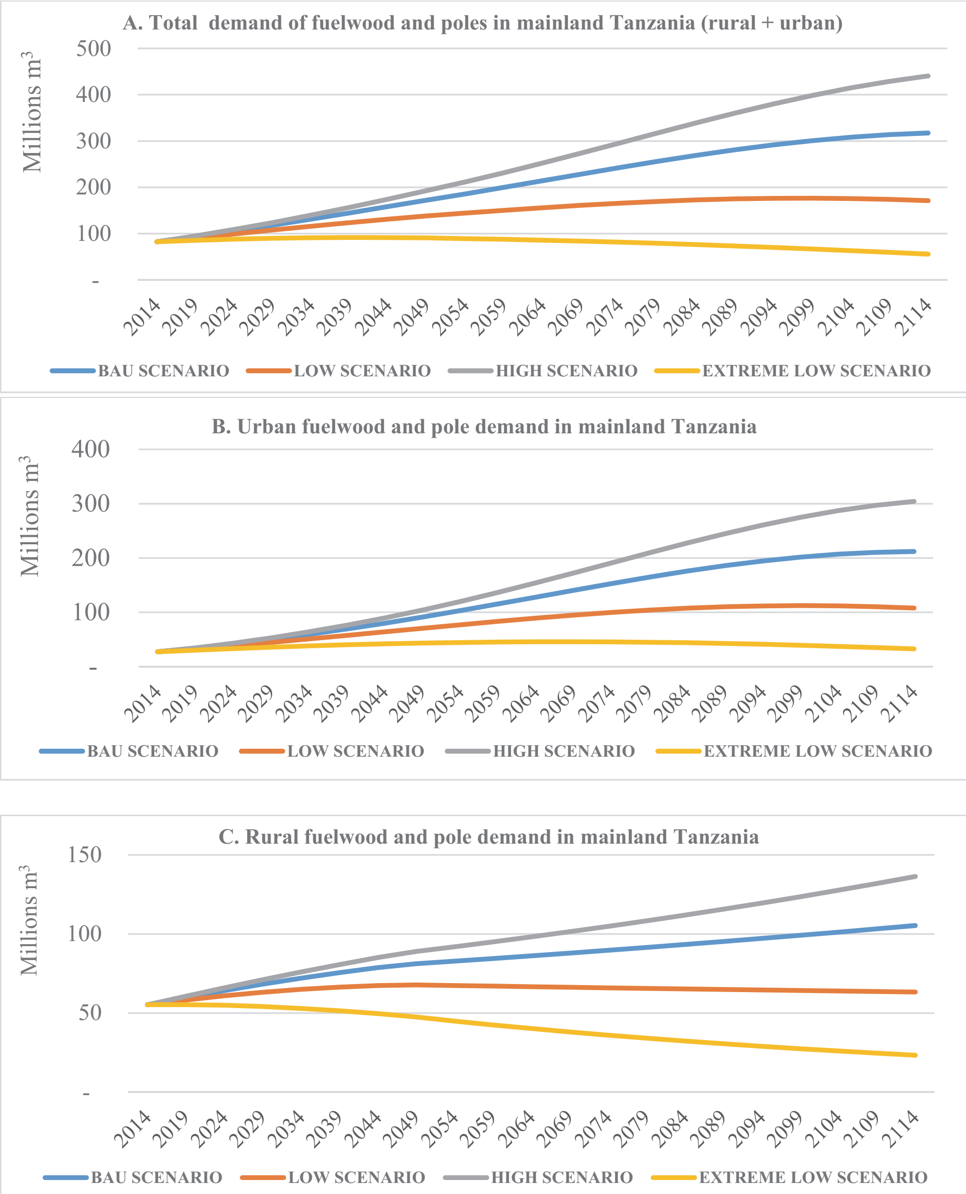


Figure 7: *Fuelwood and pole demand in mainland Tanzania in each of four main scenarios defined in section 2.1.2 assuming no wood supply constraints (million m*^{3} *per year).* ***A.*** *Total demand in rural and urban areas.* ***B.*** *Demand in urban areas only* ***C.*** *Demand in rural areas only*

3.3 Sustainability of the Low, Base and High scenarios during 2014 - 2059

Results so far identify that 2% annual technological improvements is required to stabilize demand at or below the 100 million m^3 level; this is unlikely. Similarly, the potential long-run sustainability issues leading to the use of reserved and protected forest land to the extent as shown in section 3.1, is not likely to take place in practice as it would likely generate both national and international policy reactions. In this section we therefore concentrate on the period 2014-2059 and analyse forest sustainability impacts of each of the three scenarios Base, Low and High defined in section 2.1.2, assuming that harvest only can take place in forest areas presently allowed for harvests. Figure 8 highlights sustainability criteria in the form of (a) total inventory in both protected area and harvestable areas, (b) nationwide harvestable inventory, and (c) harvest level of wood for firewood, charcoal and poles. The harvest levels of the Low, Base, and High scenarios culminate in 2059 harvest levels of 148, 192, and 219 million m^3 respectively. These harvest increases of 1.8, 2.4, and 2.8 times the 2014 levels lead to a 2059 harvestable inventory level that is 92%, 68%, and 46% of initial levels for the Low, Base and High scenarios respectively. In each case the total inventory rises as volume accumulates in forest reserves, nearly doubling.

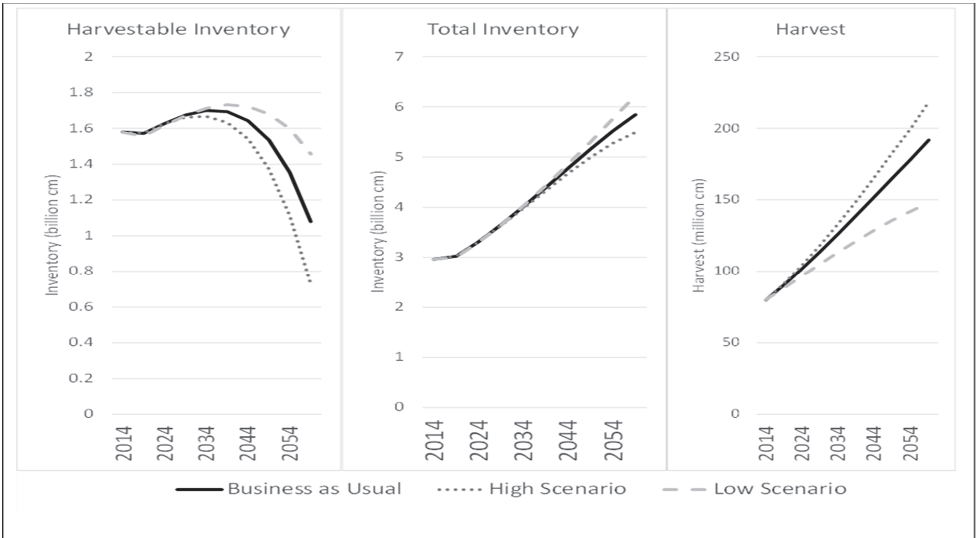


Figure 8: *Development in mainland Tanzania of (a) forest growing stock in areas where harvest is allowed, (b) forest growing stock in both protected area and harvestable areas, and (c) harvest level of wood for fuelwood, charcoal and poles during 2014-2054 for the Low, Base and High scenarios assuming no harvest in forest reserves and protected land*

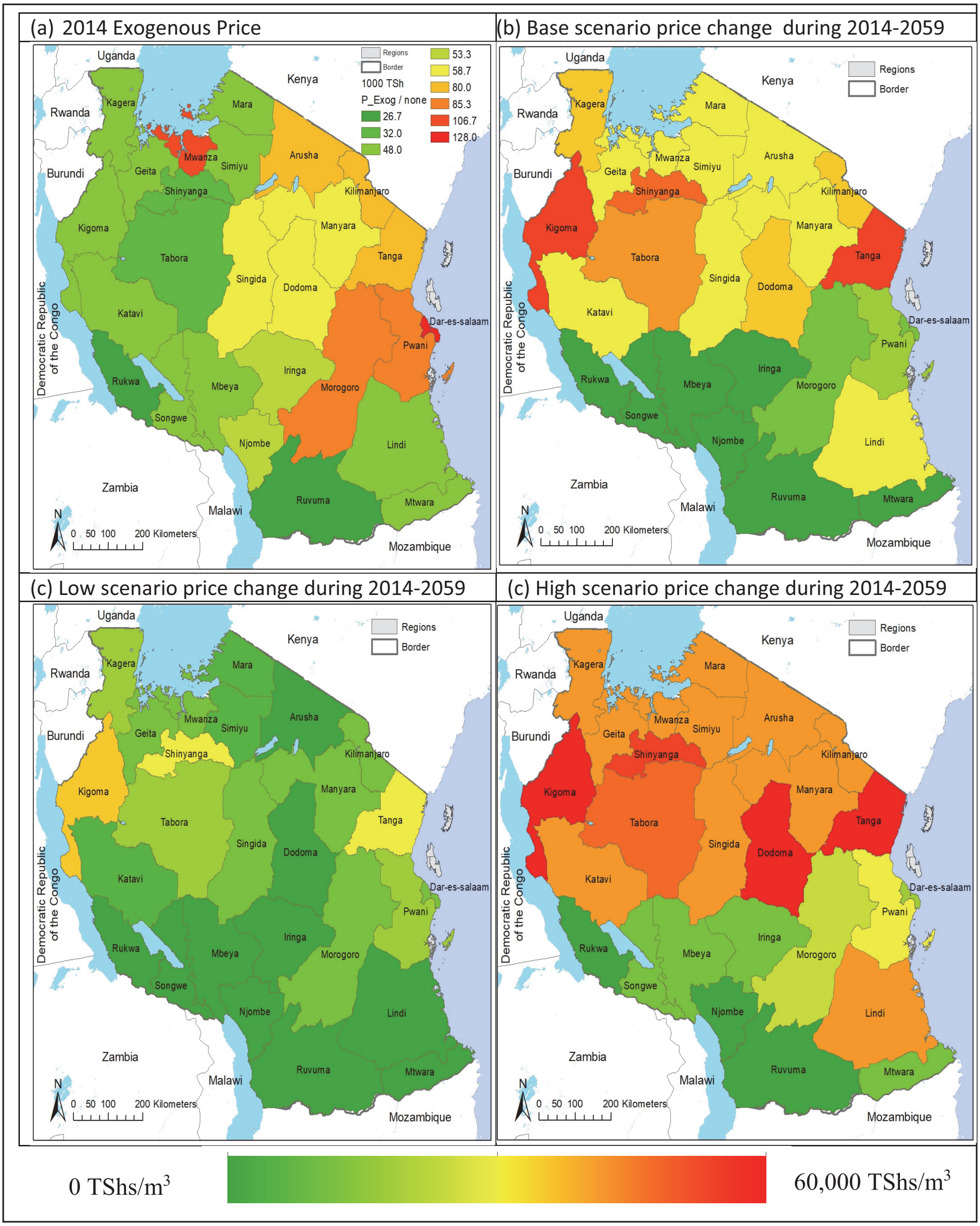


***Figure 9**: Regional prices of fuelwood used for charcoal production in base year 2014 (a) and the corresponding price changes from 2014 to 2059 in the scenarios Base (b), Low (c) and High (d) in '1000' Tshs per m^3 fuelwood used for charcoal production*

The four panels of Figure 9 highlight the exogenous starting price in 2014 for charcoal in each Tanzanian region along with the change in the charcoal prices over the 2014-2059 time period, measured in thousand Tshs per m^3 fuelwood used for producing charcoal.

Figure 9a shows the geographic distribution of charcoal prices which are higher in the east due to the dominance of the Dar es Salaam. The other area of higher prices is Mwanza region, which is the second largest charcoal market in the country. Figure 9b demonstrates that the future increases in price are manifested not in the actual regions of highest demand (Dar es Salaam and Mwanza) but rather in the adjacent regions which serve as supply zones to the larger markets. With the exception of Lindi, the north part of the country experiences price increases whereas the south sees little real price increase. The Low scenario price change map of Figure 9c avoids the degree of price increases of the Base scenario with the largest price increases contained in the Kigoma region where the 34,000 TShs/m^3 increase constitutes a 70% real price increase over its 48,000 TShs/m^3 price in 2014. The High scenario shown in Figure 9d leads to price increases as high as 60,000 TShs/m^3 in all regions except the southeastern regions.

4 DISCUSSIONS

4.1 Main results

The results of our analysis shown in Figures 4-9 indicate all how strong the demand for fuelwood is in Tanzania. The high population growth and urbanization rates shown in Figure 3 are important drivers of this demand, together with limited wood supply and low efficiencies in both charcoal production and consumption. A main message is shown in Figure 7 that a 2% p.a. increase in these efficiencies will needed to stabilize the future wood demand on its present level. It is also noteworthy as illustrated in Figure 6, that about 45% of the charcoal demand in mainland Tanzania derives from the Dar es Salaam region and that this portion is rather stable over time.

For the starting year 2014 of our analysis we get, based on the assumptions specified in section 2.2, a total consumption of fuelwood (i.e. wood for firewood and charcoal) and poles of 83 million m^3. URT (2015a:47) reports an annual harvest of 62.3 million m^3 of wood including industrial wood harvest, and FAO (2018) gives a total harvesting volume in 2014 of 40.2 mill m^3 when calculated as assumed in section 1.1. We have no explanations why we get so much higher harvest figures in 2014 than URT (2015a) and FAO (2018). Our assumptions are clearly specified, but the assumptions underlying the other two studies have not been possible to get. Future empirical research regarding consumption of these products, is required.

Nevertheless, the future increase in the production and consumption of fuelwood, poles and charcoal found in this study is alarming. Even in the Low consumption scenario, where we have assumed rather strong technological improvements, we see decreasing growing stocks in the areas allowed for harvests.

The TanzFor model as applied here links in an economic consistent framework supply and demand for fuelwood, poles and charcoal, and has as first study in Africa applied data at forest plot level from a detailed national forest inventory (NAFORMA) and newly developed growth functions as basis for the wood supply.

4.2 Uncertainty

Results of a modeling exercise such as this depend in large part upon the underlying assumptions stated in section 2. While these assumptions are based on best available data, they do of course include considerable uncertainty. On the wood supply side we have used the NAFORMA data, and to the best of our knowledge this is the best available National Forestry

Inventory data in Africa. On the demand side we have utilized projections of urban and rural population growth combined with assumed technological improvements. The future total population growth is uncertain, but has an inertia which makes large changes of our estimates not very likely. Higher uncertainty is most likely linked to the assumed urbanization rates, which increase significantly the demand for charcoal.

Another component of uncertainty relates to what we in section 2 have labelled technological improvements. This directly includes more efficient charcoal production and consumption, but also indirectly assumptions about substitution of fuelwood and charcoal for other energy carriers in the cooking market. Examples of such substitutes in Tanzania are increased use of electricity and LNG gas. For the moment these products are not economically competitive with charcoal and fuelwood, but this may change depending on capacity investments and future producer and consumer policies. TanzFor model could be used for analyzing impacts of such policies. However, we have not come across any study in Tanzania where such substitution elasticities have been analysed; if reliable data were available we could easily incorporate substitution in TanzFor through for example income demand elasticities, where negative income demand elasticities for charcoal would give decreased charcoal consumption per capita as per capita income increases over time.

Instead, in this paper, technological change is included through assumed annual average technological improvements in production and consumption as specified in section 2.1.2 and Appendix 2. The realism in these assumptions can be discussed. For example, the 0.5% p.a. improvement assumed in the Business as Usual (BAU) charcoal consumption scenario means that the charcoal consumption per capita in 2114 will be about 61% of the per capita consumption in 2014, whereas the per capita income in 2114 assuming a per capita income growth of 3% p.a. will be about 19 times the 2014 per capita income. In the Low charcoal consumption scenario the assumed technological improvement of 1% p.a. implies that the per capita consumption of charcoal in 2114 will be 37 % of the per capita charcoal consumption in 2014. This illustrate the uncertainty associated with assumptions of technological, particularly in long-term analyses like here having a 50-100 years perspective.

This study has concentrated on the three products charcoal, fuelwood and poles only. However, other main forest products such as sawnwood (hardwood and softwood), pulp and paper, fibreboard, particleboards and plywood are of growing importance in Tanzania, and are already included in the TanzFor model. Of these products, the incorporation of hardwood sawnwood (and plywood) is likely to be most important related to the fuelwood and charcoal results analysed in this paper, as branches of hardwood harvested trees often and easily are used for bioenergy. Softwood sawntimber, particleboard, plywood and pulp production are based on softwood plantations providing residues which are not in high demand for fuelwood and charcoal in Tanzania, at least at present.

Illegal logging is one uncertainty factor common for all scenarios analysed. Very few published studies have quantified illegal tree cuttings and logging for charcoal, poles or fuelwood productions in Tanzania. However, the TRAFFIC project reports (Milledge and Elibariki, 2005; Milledge and Kaale, 2005: Milledge *et al*., 2007) show that illegal timber harvests could be 30–70% of total harvest in the miombo woodlands. Such high shares may mislead both statistics, conclusions and policy recommendations. Illegal logging is linked to challenges regarding utilization of common pool resource land, discussed some further in the next section.

4.3 Relevance of forest sector modelling in Tanzania

The expected main advantage of developing the forest sector model - TanzFor is rather clear: It should give an appropriate tool for providing bio-economic analyses which consistently combine (a) detailed forest growing stock data from NAFORMA, (b) forest growth data from recent forest yield research like Mugasha *et al*. (2017), and (c) socio-economic data which determine the demand for charcoal and firewood, like population growth, economic growth, urbanization rates, transport costs, and technology changes. With such a tool it should be possible to analyse more realistically than before how changes in any of the assumed model input factors, and policies, may influence the Tanzanian forest sector, for example as done in this paper.

This advantage comes with the uncertainties described above in section 4.2, and one should ask how relevant it is to apply an intertemporal dynamic forest sector model like TanzFor in a developing country like Tanzania. Handling uncertainties regarding model input data in forest sector models are discussed rather detailed in Kallio (2010), Chudy *et al*. (2016), Jaastad *et al*. (2018) and Buongiorno and Johnston (2018). One conclusion common for these studies is that ordinary sensitivity analyses and Monte Carlo simulations are the most realistic ways of dealing with uncertainty in forest sector models. TanzFor is a dynamic forest sector model, i.e. optimizing over the whole analyzing period, in contrast to the so called dynamic-recursive forest sector models which apply only static optimization for each period. Each simulation in TanzFor model takes a long time, and providing many hundreds of runs as required in Monte Carlo simulations, is not realistic with TanzFor at present available computer capacities. We are therefore left with sensitivity analyses as the best way of getting information on how uncertainties in TanzFor model input data influence the model results.

The agent behavioral assumptions made in forest sector models are discussed in e.g. Latta *et al.* (2013) and Sjølie *et al.* (2011a,b). It is beyond the scope of this study to go into details here. However, it is questionable to assume for a developing country like Tanzania that agents have perfect information and that free competition prevails in the forest sector, as is the case in TanzFor. As such, the TanzFor results should be interpreted as optimal solutions under the two strong assumptions that the agents involved (i.e. charcoal and firewood producers and consumers, transport providers) have perfect foresight and that free competition prevails. This means that the TanzFor results are likely to give some lower market prices and higher market quantities of charcoal and fuelwood than what would be the case in "real life".

It seems reasonable to assume that information about present prices is well known, as e.g. the availability and coverage of mobile phones in Tanzania is good. The assumption of full knowledge about future prices and quantities is, however, unrealistic. To reduce this problem, Latta *et al*. (2013) propose to combine static and intertemporal optimization forest sector models into hybrid models which *"could move sequentially through time utilizing the intertemporal optimization model solution for harvest levels, manufacturing capacity additions, and silvicultural investment then use those outputs to guide the recursive dynamic model's short-run solution which would then, in turn, update the starting conditions for the intertemporal optimization solution in the next time period"*. In the case of Tanzania this would require to develop a recursive dynamic forest sector model for Tanzania and combine that with TanzFor. In principal that would not be difficult, because all model input data necessary for a recursive dynamic model would be available from TanzFor; however, in practice this was not possible within the time limits for this study.

In TanzFor the opportunity cost of postponing the harvest is included through the assumed time-dependent optimization objectives, whereas in reality fuelwood harvesting on Common Pool Resource (CPR) land is focused on present profit generation and may not consider the future development of the harvested forest area. Thus, if the majority of fuelwood harvests in Tanzania originate on land exhibiting strong CPR characteristics, the TanzFor modeled harvesting might be lower than what would happen in real life. With TanzFor, the assumed choice of interest rate will influence the strength of this impact – the higher the assumed interest rate is, the closer the model results will be to "pure" CPR behaviour. This behavior can also be approximated by lowering the harvest costs in the model.

The main challenge regarding analyzing fuelwood harvest on CPR land is that impacts of non-market goods and services like e.g. biodiversity, water availability and erosion are not considered when harvests are decided. There is a substantial literature base focusing on resource utilization on CPR lands (see e.g. Agrawal, 2003; Adams *et al*., 2003; Ostrom, 2009, 2008, 1990; Ostrom *et al*., 1994 etc.), and it is beyond the scope of this paper to go into detailed discussions of these matters. However, it should be noted that the structure of the TanzFor model allows for a variety of methods by which non-market values can be considered - for example as extra costs of harvest, or as obliged regeneration costs depending on harvest intensity, or as harvest constraints on certain vegetation or property types. Likewise, the model allows for introducing additional costs associated with enforcement and monitoring necessitated by policy changes designed to alter harvests or behaviour. By including relevant costs and benefits, TanzFor model can be used to analyse the overall preferability of introducing new forest land policies.

Summing up, we would like to conclude here that even if intertemporal models like TanzFor and also recursive-dynamic models have several weak points as described above, better alternative quantitative methods for analysing main supply and demand interactions in the Tanzanian forest sector over time do not exist to our understanding. An important point is to interpret the results of the models with their weaknesses in mind.

4.4 Policy implications

The primary objectives of this study was to develop the forest sector model TanzFor and show some preliminary applications of the model and discuss future promising research tasks. As such, one should be careful in drawing policy implications of the results, but it seems fair to say that the three case studies shown in this study indicate rather strongly that charcoal production and consumption are important in Tanzania and create a huge pressure on the forests. As such, the strong linkage between charcoal and the environment needs to be considered during planning and decision making processes. The sustainability of charcoal production will depend on proper policy instruments put in place and adhered to. The Government of Tanzania has at different times tried to increase taxes on charcoal, and ban charcoal production and transport between districts, but so far with limited effects. It is beyond the scope of this article to propose new policies, but we would like to emphasize that the TanzFor model documented in this paper, could be of high interest to use for analyzing impacts of various policy means proposed to meet the charcoal challenges in Tanzania. Most likely, mixed policy efforts will be required, including for example subsidization of cleaner energy technologies in charcoal production and consumption, establishment and promotion of plantations (*Acacia Mearnsii* and *Eucalyptus* species) specifically for charcoal production in degraded lands. Increasing charcoal prices alone without providing reliable alternatives will likely result in increased illegal production and trade.

As mentioned in several of the papers analyzed in Nyamoga and Solberg (2019), many other policy means have been proposed for getting a more sustainable fuelwood sector in Tanzania. In our opinion TanzFor is very suitable for analyzing impacts of policy means as differences over time between model results with and without the policy or set of policies being analyzed. Almost all kinds of quantitative policy means can be incorporated in TanzFor and be evaluated with respect to their effectiveness and efficiency, as well as distributional impacts.

4.5 Promising future research

Many interesting tasks for future research connected to the use of TanzFor model have come up during this study, the following being among the most interesting ones.

Further use of the NAFORMA data

In this study only NAFORMA's data on forest growing stock and area distribution have been used, and the already collected data regarding carbon content in soils from permanent plots in NAFORMA have yet not been used. If included in TanzFor, this carbon data together with the already implemented data in the model, would make possible complete carbon accounting for the whole of Tanzania's forest sector. The same is the situation regarding utilizing the social survey part of the NAFORMA data. Many thousands households have been surveyed in NAFORMA regarding their use of forest and fuelwood, and the collected data if properly analysed, could give very valuable information about household fuelwood consumption based on thorough statistical sampling covering all regions of Tanzania.

When re-measurements of NAFORMA are completed, one would in addition get possibilities of estimating also the change over time regarding forest growth, carbon sequestration in soil, land degradation, and harvest and consumption of fuelwood and sawlogs in each region and country aggregates. These data will be very useful for calibrating the present applied forest growth models, carbon sequestration rates and fuelwood consumption changes, and improving TanzFor.

Provide more accurate data on the consumption of charcoal and firewood

The studies reviewed in Nyamoga and Solberg (2019) reveal large variations in the estimates of present per capita consumption in Tanzania of both charcoal and firewood, as well as on factors deciding the consumption. More research is needed here, covering the whole country and being built on proper theories of household behavior. For this, as already mentioned, utilizing the rather detailed data available in the social survey part of NAFORMA could be interesting. Another way would be to get charcoal and firewood more explicitly included in the official national household surveys being conducted in Tanzania. A third way is to perform studies like Nyamoga *et al*. (2019) in other urban areas of Tanzania. Such surveys should in addition to sample stratifications on income, also try to stratify on households which during the last 2-3 years have changed their main type(s) of cooking energy. As such, one could get improved empirical information about which main factors influence such changes, and thus provide a better basis for prognosis about the future fuelwood and charcoal consumption development, and for improved policy making.

Improving the structure of TanzFor and forest sector modelling in Tanzania

All the above mentioned research tasks would contribute to improving forest sector modelling in Tanzania. Existing forest plantations are already included in NAFORMA and TanzFor, but possibilities of investing in new forest plantations of various kinds are not included in the present version of TanzFor. This however, would be relatively easy to implement and should be incorporated in a revised model version. The same is the situation regarding soil carbon sequestration, which also rather easily could be included in TanzFor using existing NAFORMA data.

NAFORMA includes all forests in mainland Tanzania described at plot level, and if appropriate biodiversity indicators were developed, one could use TanzFor for analysing also how biodiversity would be impacted by for example varying harvest developments in indigenous forests, new investments in forest plantations, or expanding other cooking energy carriers like electricity.

It would also be very interesting to develop a recursive-dynamic forest sector model for Tanzania based on the data input in TanzFor, in order to check how important the assumptions of perfect foresight is for a country like Tanzania – cf. the citation in section 4.2 from Latta *et al*. (2013).

Applying TanzFor in policy and climate analysis

If the above suggested improvements of TanzFor were made, the model would include the whole carbon cycle of Tanzania's forest sector, as well as other important sustainability factors like forest biodiversity, land erosion, and indoor air pollutions caused by the use of charcoal in urban areas.

As already mentioned, forest sector models are particularly useful for analyzing impacts of policy proposals. Each policy or set of policies imply different costs and benefits over time, thus giving different results regarding policy effectiveness and efficiency as well as distributional impacts. Using TanzFor to estimate such impacts, the model could prove to be a very useful tool for policy makers in searching for appropriate land-use policies, being it REDD+ policies or other related to sustainable land-use in Tanzania.

5 CONCLUDING REMARKS

In this study we have constructed an intertemporally optimized spatial partial equilibrium model of the Tanzanian forest sector (TanzFor) and applied it for analyzing forest sustainability of alternative scenarios of the future development of the country's consumption and production of firewood, charcoal and wooden poles. TanzFor as applied here links in an economic consistent framework supply and demand for fuelwood, poles, charcoal, sawnwood and other forest industry products. As first study in Africa TanzFor applies data from a detailed National Forestry Inventory - NAFORMA and newly developed growth functions as basis for the wood supply.

The future increase in the production and consumption of fuelwood, poles and charcoal found in this study is alarming. Even in the Low charcoal consumption scenario, where rather strong technological improvements both regarding production and consumption of charcoal are assumed, we see decreasing growing stocks in the forest areas allowed for harvests.

Many interesting research tasks exist for improving this type of analyses in Tanzania. Discussing this, we recommend giving priority to the following tasks: Further use of the NAFORMA data, provide more accurate data on the present and future consumption of charcoal and firewood, provide analysis of property regimes' effect on wood supply, improve TanzFor and apply it in policy analysis and analyses related to forest climate change mitigation and adaption in Tanzania.

6 ACKNOWLEDGEMENT

We extend our gratitude to the Norwegian Government through the Higher Education Loan Board (Lånekassen) and the Norwegian University of Life Sciences through the Faculty of Environmental Science and Nature Management (MINA) for financing the data collection in Tanzania and handling all the logistics during the research period. We also thank the Government of the United Republic of Tanzania through Sokoine University of Agriculture for granting the study leave to the PhD Student and offering the research permit to conduct field works and data collection in Tanzania. The entire contents in this article should not be taken by any means to reflect the views of Norwegian University of Life Sciences (NMBU) or Sokoine University of Agriculture (SUA), as the authors are solely accountable and responsible for the contents.

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8 APPENDICES

Appendix 1: Mathematical description of TanzFor

This appendix gives a formal specification of TanzFor. The first part lists symbols used in the paper and has been organized into three groupings; sets, parameters, and variables. Sets, for which we have used lower case letters, are collections of sub-sets overs which the model is defined. Parameters, again designated by lower case letters, represent exogenous data which may or may not be defined over a group of sets. Finally, upper case letters indicate endogenous variables determined by the model which may or may not be defined over a group of sets. Then follows the procedures for the piecewise integration of the product demand curves followed by specification of the objective function and constraints that comprise TanzFor.

1. Sets

- f is the set of forest silvicultural regimes which include a no harvest option along with a clear-felling or partial harvest option for each time period
- n is the set of 15,180 National Forestry Resources Monitoring and Assessment (NAFORMA) forest inventory plots
- p is the set of forest products either produced or consumed within the model
- r is the set of 25 Tanzanian regions
- s is the set of g equal steps over which the area under forest products demand is broken into
- y is the set of 20, 5-year time periods, y^{-1} would indicate the first time period *(2014-2019)*

2. Parameters

- a_n forest area in hectares parameter for NAFORMA plot n
- b bound limiting piecewise integration to above $1/b$ of exogenous product price e
- c_{py} parameter indicating the forest product non-wood costs of manufacturing product p in year y
- d_{rpy} exogenous demand quantity in region r for product p in year y used to locate the constant elasticity demand curve
- e_{rp} exogenous price in region r for product p used to locate the constant elasticity demand curve
- g number of steps, or rectangles, used in the piecewise integration of the product demand curves
- h_{rpys} parameter indicating the height of each rectangle associated with of the s equal steps that are used in the piece-wise integration of the area under the demand curve for forest product p in region r in time period y
- i parameter indicating the discount rate (%)
- m_{py} parameter indicating the exogenous foreign imports or forest product p in time period y
- $o_{p'p}$ parameter indicating forest product manufacturing coefficient indicating amount of forest product p required to produce one unit of product p'
- q maximum quantity bound multiple limiting piecewise integration to q times exogenous demand quantity d
- $t_{pr'r}$ parameter indicating the per unit cost of transporting product p from region r' to region r
- u upper bound limiting piecewise integration to u times the exogenous product price e

v_{nfy} parameter indicating clear-felling harvest yield on NAFORMA plot *n* enrolled in forest silvicultural regime *f* in time period *y*

w_{rpys} parameter indicating the width of each rectangle associated with of the *s* equal steps that are used in the piece-wise integration of the area under the demand curve for forest product *p* in region *r* in time period *y*

x_{py} parameter indicating the exogenous foreign exports or forest product *p* in time period *y*

z_{nfy} parameter indicating partial harvest yield on NAFORMA plot *n* enrolled in forest silvicultural regime *f* in time period *y*

σ_p price elasticity of demand for product *p*

3. Variables

A_{nfy} variable indicating area in hectares of NAFORMA plot *n* assigned to silvicultural regime *f* assigned a regeneration harvest in year *y*

C_y variable indicating the sum of transportation and manufacturing costs in time period *y*

D_{rpys} variable indicating the proportion of each of the *s* equal steps that the area under the demand curve in region *r* for forest product *p* in time period *y*

H_{rpy} variable indicating the annual harvest in region *r* for forest product *p* in time period *y*

I_{rpy} variable indicating the annual foreign imports to region *r* for forest product *p* in time period *y*

M_{rpy} variable indicating manufacturing in region *r* of forest product *p* in time period *y*

$R_{nfy'y}$ variable indicating area in hectares of NAFORMA plot *n* assigned to silvicultural regime *f* regenerated in year *y'* and assigned a regeneration harvest in year *y*

S_{rpy} variable indicating the annual supply in region *r* for forest product *p* in time period *y*

$T_{r'rpy}$ variable indicating the trade of forest product *p* inside Tanzania between region *r'* and region *r* in time period *y*

W_{rpy} variable indicating the annual waste or unused production in region *r* for forest product *p* in time period *y*

X_{rpy} variable indicating the annual foreign exports from region *r* for forest product *p* in time period *y*

4. The model equations

The TanzFor model consists of an objective function that implements piecewise integration of the forest product demand curves allowing for solution as a linear programming problem and nine sets of constraints controlling area allocation, harvest calculation, supply and demand balancing, and cost accounting.

The demand is determined by constant elasticity of scale (CES) demand functions. Such functions would normally require a nonlinear optimization to calculate the area under the curve. To avoid the computation issues associated with nonlinear optimization and instead solve the problem using linear programming we employ the technique of piecewise integration of the demand curve integral. This is accomplished by breaking the area under the demand curve into a number of pieces, or rectangles, with heights h_{rpys} and widths w_{rpys} that can be calculated using the demand elasticities σ_p and exogenous prices e_{rp} and quantities d_{rpy} prior to optimization. The optimization then involves the determination of the proportion of these rectangles such that the sum of the quantity dimensions (widths in our case) times the proportion of each rectangle D_{rpys} (bounded by 1 in Equation A14) must equal the total consumption quantity. The demand integral is likewise the optimal proportions of each rectangle multiplied by the area (price time quantity) of each rectangle in Equation A5.

One issue with using linear approximations of constant demand integrals is that an area over which to integrate must be defined a priori. We employ a demand integration process by which the number of steps g, maximum price multiple or height u, and lower bound on price multiple b allow flexibility in the level of detail in the piecewise integration process. Equations A1 sets the width of the first rectangle to that the price would equal the upper price limit multiple u. Equation A2 then sets the height of that first rectangle to that maximum price. Equations A3 and A4 then calculate the width and midpoint height of each of the remaining g-1 rectangles.

$$w_{rpy1} = d_{rpy} * u^{\sigma_p} \quad \forall r,p,y$$ Width of first demand integral rectangle, s=1 (A1)

$$h_{rpy1} = u * e_{rp} \quad \forall r,p,y$$ Height of first demand integral rectangle, s=1 (A2)

$$w_{rpys} = \frac{\min\left(q * d_{rpy}, d_{rpy} * \left(\frac{1}{b}\right)^{\sigma_p}\right) - w_{rpy1}}{g-1} \quad \forall r,p,y,s>1$$ Width of demand integral (A3)

$$h_{rpys} = e_{rp} * \left[\frac{\sum_{s^*<s} w_{rpys^*} + \frac{1}{2} * \frac{\min\left(q * d_{rpy}, d_{rpy} * \left(\frac{1}{b}\right)^{\sigma_p}\right) - w_{rpy1}}{g-1}}{d_{rpy}}\right]^{\left(\frac{1}{\sigma_p}\right)} \quad \forall r,p,y,s>1$$

Height of demand integral rectangle (A4)

Objective function

The objective function (Equation A5) used in the linear program is the maximization of the discounted sum of the net social surplus.

$$MAX \quad \sum_{y}\left(\sum_{r}\sum_{p}\sum_{s}\left(D_{rpys} * w_{rpys} * h_{rpys}\right) - C_{y}\right) * (1+i)^{-(y-y^{1})} \qquad \text{(A5)}$$

Constraints

$$\sum_{f}\sum_{y} A_{nfy} = a_{n} \quad \forall n \qquad \text{Allocation of all available area (A6)}$$

$$\sum_{y'} R_{nfyy'} = \sum_{f'}\sum_{y'} A_{nf'y'} + \sum_{f'}\sum_{y'} R_{nf'y'y} \quad \forall n, f, y \qquad \text{Allocation of all available area (A7)}$$

$$\begin{aligned} 5 * H_{rpy} &= \sum_{n}\sum_{f}\left(A_{nfy} * v_{nfy}\right) \\ &+ \sum_{n}\sum_{f}\sum_{y':y'>y}\left(A_{nfy'} * z_{nfy}\right) + \sum_{n}\sum_{f}\sum_{y':y'<y}\left(R_{nfy'y} * v_{nfy}\right) \quad \forall r, p, y \end{aligned} \qquad \text{Annual harvest calculation (A8)}$$

$$\begin{aligned} &H_{rpy} + M_{rpy} + \sum_{r'} T_{r'rpy} + \sum_{p'}\left(M_{rpy} * o_{p'p}\right) \\ &= S_{rpy} + \sum_{p'}\left(M_{rp'y} * o_{p'p}\right) + \sum_{r'} T_{rr'py} + X_{rpy} \quad \forall r, p, y \end{aligned} \qquad \text{Supply balance (A9)}$$

$$S_{rpy} = \sum_{s}\left(D_{rpys} * w_{rpys}\right) \quad \forall r, p, y \qquad \text{Demand balance (A10)}$$

$$\sum_{r} X_{rpy} = x_{py} \quad \forall p, y \qquad \text{Foreign Export limitation (A11)}$$

$$\sum_{r} M_{rpy} = m_{py} \quad \forall p, y \qquad \text{Foreign Import limitation (A12)}$$

$$\sum_{r}\sum_{p}\left(M_{rpy} * c_{py}\right) + \sum_{r'}\sum_{r}\sum_{p}\left(T_{r'rpy} * t_{pr'r}\right) = C_{y} \quad \forall y \qquad \text{Industry costs (A13)}$$

$$D_{rpys} \leq 1 \quad \forall r, p, y, s \qquad \text{Demand integral step limit (A14)}$$

5. Some more description of how the demand is calculated

Below we demonstrate that a simple CES demand curve is what Equation A4 is portraying, and in addition an example is presented of how demand is shifted over time.

The basic CES demand curve is defined as:

$$P = \hat{P}\left(\frac{Q}{\hat{Q}}\right)^{\frac{1}{\sigma}}$$

where:	P	is the endogenous price
	$\hat{P}$	is the exogenous price
	Q	is the endogenous quantity
	$\hat{Q}$	is the exogenous quantity
	σ	is the elasticity

Which is the same as Equation A4:

$$h_{rpys} = e_{rp} * \left[\frac{\sum_{s^*<s} w_{rpys^*} + \frac{1}{2} * \frac{\min\left(q * d_{rpy}, d_{rpy} * \left(\frac{1}{b}\right)^{\sigma_p} \right) - w_{rpy1}}{g-1}}{d_{rpy}} \right]^{\left(\frac{1}{\sigma_p}\right)} \qquad \forall r, p, y, s > 1$$

Height of demand integral rectangle (A4)

where:

h_{rpys} is the endogenous price P in the CES demand equation

e_{rp} is the exogenous price $\hat{P}$ in the CES demand equation

$\sum_{s^*<s} w_{rpys^*} + \frac{1}{2} * \frac{\min\left(q * d_{rpy}, d_{rpy} * \left(\frac{1}{b}\right)^{\sigma_p} \right) - w_{rpy1}}{g-1}$ is the endogenous Q in the CES demand equation

d_{rpy} is the exogenous quantity $\hat{Q}$ in the CES demand equation

σ_p is the elasticity σ in the CES demand equation

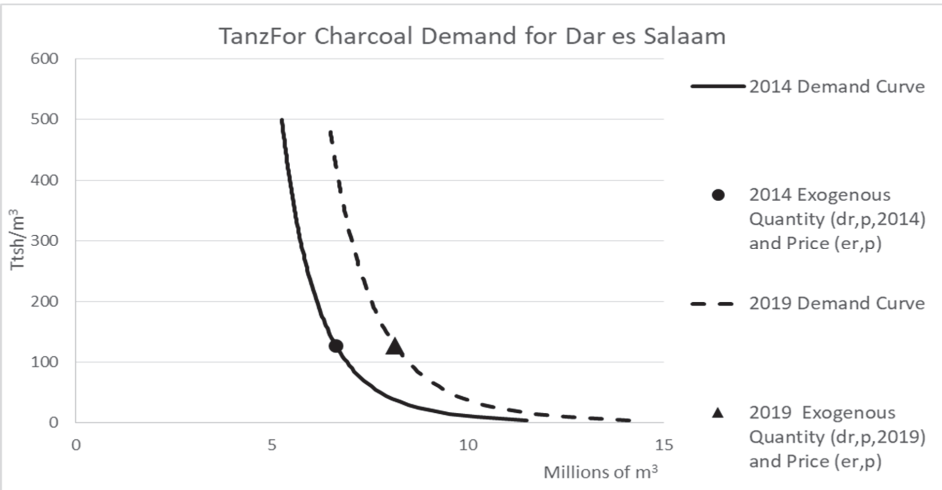
For more explanation on these matters we refer to Lebow et al. (2003):

Lebow, Patricia K.; Spelter, Henry; Peter J. Ince. 2003. FPL.PELPS. A price endogenous linear programming system for economic modeling, Supplement to PELPS III, Version 1. Res. Pap. FPL-RP-614. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 32 pp.

The CES demand curve shown above is specified with three exogenous parameters; exogenous price, exogenous quantity, and elasticity. We hold exogenous price and elasticity constant in TanzFor and shift the exogenous demand d_{rpy} based on scenarios specific changes in future charcoal production technology (how much wood is required per ton of charcoal produced) and charcoal consumption technology (household stove efficiency in kg charcoal used per capita). The table below shows how these values are calculated for the BAU scenario charcoal demand in Dar es Salaam moving between 2014 and 2019.

Measure	**2014**			**2019**		**units**
	urban	**rural**		**urban**	**rural**	
Population	4830255	37314		6229620	41441	people
Consumption per capita	183	12	Improves 0.5% p.a.	178	12	tons per year
Production Technology	7.50	7.50	Improves 0.5% p.a.	7.32	7.32	m^3 per kg of charcoal
Charcoal Demand	6629525	3358		8134171	3548	m^3 wood for charcoal
Exogenous Demand Target (d_{rpy})	**6632883**			**8137719**		**m^3 wood for charcoal**

The figure below shows how those scenario-specific exogenous demand targets are used to shift the demand curve from the 2014 location to a 2019 location.



Appendix 2: Specifications of exogenous variables for the three main scenarios Business as usual (BAU) Charcoal Consumption, Low charcoal consumption and High charcoal consumption in mainland Tanzania – cf. section 2.1.2 in the man text.

YEAR	2014	2019	2024	2029	2034	2039	2044	2049	2054	2059	2064	2069	2074	2079	2084	2089	2094	2099	2104	2109	2114
BUSINESS AS USUAL (BAU) CHARCOAL CONSUMPTION SCENARIO																					
Population growth (% p.a.)[1]	2.70	3.06	2.93	2.82	2.71	2.58	2.43	2.28	2.15	2.02	1.89	1.76	1.63	1.50	1.38	1.26	1.15	1.04	0.93	0.82	0.71
Economic growth (% p.a.)[1]	7.00	6.60	6.50	5.85	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50
Urbanization rate (% p.a.)[1]	5.47	5.22	4.89	4.59	4.28	3.94	3.68	3.45	3.11	2.80	2.52	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27	2.27
Percent of urban population (%)[1]	30.90	34.50	38.14	41.74	45.23	48.50	51.66	54.81													
Stove Efficiency - Starting point (% of total heat retention)[2]	13.00																				
Stove efficiency-Improvement(% p.a.)[3]	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Kiln efficiency - Starting point (% of total wood retained)[4]	19.00																				
Kiln efficiency- Improvement (% p.a.)[3]	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
LOW CHARCOAL CONSUMPTION SCENARIO																					
Population growth (% p.a.)[1]	2.70	2.60	2.49	2.40	2.30	2.19	2.07	1.94	1.83	1.72	1.61	1.50	1.39	1.28	1.17	1.07	0.98	0.88	0.79	0.70	0.60
Economic growth (% p.a.)[1]	7.00	5.61	5.53	4.97	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68	4.68
Urbanization rate (% p.a.)[1]	5.47	4.44	4.16	3.90	3.64	3.35	3.13	2.93	2.64	2.38	2.14	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93
Percent of urban population (%)[1]	30.90	29.33	32.42	35.48	38.44	41.22	43.91	46.59													
Stove Efficiency - Starting point (% of total heat retention)[2]	15.00																				
Stove efficiency-Improvement(% p.a.)[3]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Kiln efficiency - Starting point (% of total wood retained)[4]	19.00																				
Kiln efficiency- Improvement (% p.a.)[3]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
HIGH CHARCOAL CONSUMPTION SCENARIO																					
Population growth (% p.a.)[1]	2.70	3.52	3.37	3.24	3.12	2.97	2.79	2.62	2.47	2.32	2.17	2.02	1.87	1.73	1.59	1.45	1.32	1.20	1.07	0.94	0.82
Economic growth (% p.a.)[1]	7.00	7.59	7.48	6.73	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33
Urbanization rate (% p.a.)[1]	5.47	6.00	5.63	5.28	4.92	4.53	4.23	3.97	3.57	3.22	2.89	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61
Percent of urban population (%)[1]	30.90	39.68	43.86	48.00	52.01	55.77	59.41	63.03													
Stove Efficiency - Starting point (% of total heat retention)[2]	11.00																				
Stove efficiency-Improvement(% p.a.)[3]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Kiln efficiency - Starting point (% of total wood retained)[4]	19.00																				
Kiln efficiency- Improvement (% p.a.)[3]	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25

Sources: [1]https://population.un.org/wpp/DataQuery/

[2]Sanga and Jannuzzi (2005)

[3]Our best intellectual guess based on literature review and field experiences

[4]Malimbwi *et al.,* (2007) and Van Beukering *et al.*, (2007)

[5]URT (2017) - Energy Access Situation Report by the year 2016 for mainland Tanzania

Appendix 3: Production costs, transport costs and market prices

3.1 PRODUCTION COSTS

The average production costs are summarized in table A_1, A_2 and A_3 below. The estimation were based on the survey conducted in 2015 from producers and traders from selected regions in Tanzania. To convert the production costs into USD we used the average exchange rate of Tshs. 1726 reported by the Bank of Tanzania in January 2017.

Table A_1: Average unit production costs for forest products as per year 2014/2015

Product	Costs (Tshs)	Costs Equivalent USD	Unit
SWHARD	1,119,000	648	M^3
SWSOFT	433,800	251	M^3
POLESHARD	351,000	203	M^3
POLESSOFT	351,000	203	M^3
CHARCOAL	5,600	3	Bag
PPAPER	1,260,000	730	Tonne

Source: Own data collection (2015)

Table A_2: Average production costs for charcoal in 2014/2015

S/No.	Category	Average Costs/Bag (Tshs)
1	Tree Cutting Costs	500
2	Logs Processing	500
3	Logs Collection	450
4	Transport to Kiln	650
5	Kiln Preparation	750
6	Kiln Supervision	560
7	Kiln Construction	1 200
8	Axe Price	250
9	Hoe Price	140
10	Rake Price	250
11	Spade Price	200
12	Other Costs	130
	Total Average Costs	**5 600**

Source: Own data collection (2015). The assumed weight is 50 kg per bag

Table A_3: Estimated production costs for poles in Mafinga, Iringa region

Pole Size (Lenth)	Purchasing	Seasoning	Treatment	Transport	Total Costs
9M	80 000	7 500	50 000	35 000	172 500
10M	100 000	7 500	65 000	40 000	212 500
11M	120 000	7 500	100 000	62 000	289 500
12M	130 000	7 500	150 000	62 000	349 500
13M	140 000	7 500	200 000	80 000	427 500
14M	150 000	7 500	250 000	80 000	487 500
15M	160 000	7 500	250 000	100 000	517 500
Average	**125 700**	**7 500**	**152 200**	**65 600**	**351 000**

Source: Own Field Data Collection (2015)

The pole production costs are based on own survey conducted in summer 2015 among producers in Iringa region to determine the production costs and the market prices at producer gate for poles. The total production costs averaged Tshs. 351,000, while the market price ranged between Tshs. 234,000 - 625,000 and averaged Tshs. 402,600 depending on the size of the pole. In the modelling the average cost and price were assumed.

3.2 TRANSPORT COSTS

Main Assumptions used in the estimation

- Transport costs were calculated using the truck hiring costs and the maximum total volume carried by such a vehicle
- The car hiring costs were obtained from timber dealers as well as transporters
- Then the computation were: Transport Costs = Car hiring costs/ Total Volume
- The truck can carry about 70% of the Maximum capacity depending on other factors
- Therefore the carrying capacity per truck load of sawnwood for hardwood was estimated to 18m^3 and for softwood to 40m^3 for trucks of the maximum capacity of 30 tonnes
- We then used the distance between regions, the hiring costs and the truck capacity to estimate the average transport costs in Tshs/ m^3/Km

i) Sawnwood

We therefore found based on the data from the surveyed sawmillers and traders that the average transport costs in Tshs/ m^3/Km was:

(a) Hardwood sawnwoood = 328 Tshs/m^3/Km
(b) Softwood sawnwoood = 148 Tshs/m^3/Km

ii) Charcoal

Based on the survey from charcoal producers and transporters in Morogoro, the average transport costs per bag from charcoal production centers in Morogoro to urban markets were:

(a) To Dar es Salaam = 46 Tshs/Bag/Km (0.046 Tshs/Tonne/Km)
(b) To Morogoro Town = 85 Tshs/Bag/Km (0.085 Tshs/Tonne/Km)

The overall average transport cost is therefore 0.065Tshs/Tonne/Km.

iii) Poles

(a) Poles – Electric poles = 380 Tshs/m^3/Km
(b) Poles – Construction = 170 Tshs/m^3/Km

iv) Pulp and Paper

The transport costs for pulp and paper was 260 Tshs/Tonne/Km

v) Firewood

For the firewood consumption in rural areas we assumed zero transport costs, because we assumed that individuals and households there collected it themselves without costs. For the transport of firewood sold in urban areas, we assumed the same transport costs per tonne as for charcoal.

3.3 FOREIGN TRADE

For the TanzFor analysis we hold export and import constant at 2014 volumes as shown in Table A4.

Table A4: Forest product trade volumes used in the TanzFor Model (1000 m^3/year)

Product Name	Import	Export
Coniferous sawnwood	0.86	6.02
Non-coniferous sawnwood	20.96	51.01
Pulp and Paper	149.90	64.50
Charcoal	0.02	0.31

Source: Governmental reports and own data collection (2015)

3.4 DEMAND ELASTICITIES FOR PRICE

The estimation of price- and income elasticities for individual products is challenging in developing countries like Tanzania due to scanty information for each specific product. In the TanzFor model, we use the charcoal price elasticity of -0.17 based on Nyamoga et al. (2019) and the price elasticities estimated in Buongiorno et al. (2003) for developing countries for sawnwood and other forest industry products. The elasticities applied are summarized in Table A5. No income elasticities were used in this study.

Table A5: Elasticities used in the TanzFor Model

Product Name	Price Elasticity
Coniferous sawnwood	-0.46
Non-coniferous sawnwood	-0.07
Coniferous poles	-2.56
Non-coniferous poles	-2.56
Pulp and Paper	-0.29
Charcoal	-0.17
Fuelwood	-0.17

Source: Own Field Survey and Buongiorno *et al.* (2003)

3.5 EXOGENOUS PRICE

The exogenous prices used in TanzFor are shown in Table A6.

Table A$_6$: Exogenous regional prices in 2014 used in the constant elasticity demand curves of the TanzFor

Region	TanzFor Product					
	SWHARD	SWSOFT	POLESHARD	POLESSOFT	CHARCOAL	PPAPER
	------1000 Ttsh/m^3------					
DaresSalaam	1649	515	403	403	128	1400
Morogoro	1570	472	403	403	85	1400
Pwani	1135	472	403	403	85	1400
Lindi	1065	440	403	403	48	1400
Mtwara	1055	440	403	403	48	1400
Ruvuma	1308	440	403	403	27	1400
Rukwa	1308	440	403	403	27	1400
Njombe	1308	471	403	403	53	1400
Iringa	1308	471	403	403	53	1400
Mbeya	1308	471	403	403	48	1400
Manyara	1308	515	403	403	59	1400
Dodoma	1308	515	403	403	59	1400
Singida	1308	515	403	403	59	1400
Mara	1308	515	403	403	48	1400
Simiyu	1308	515	403	403	48	1400
Mwanza	1308	515	403	403	107	1400
Kagera	1308	515	403	403	48	1400
Geita	1308	515	403	403	48	1400
Tabora	1308	515	403	403	32	1400
Shinyanga	1308	515	403	403	32	1400
Kigoma	1308	515	403	403	48	1400
Katavi	1308	515	403	403	48	1400
Kilimanjaro	1649	549	403	403	80	1400
Arusha	1649	555	403	403	80	1400
Tanga	1649	520	403	403	80	1400

Source: Own data collection (2015)

ISBN: 978-82-575-1610-9
ISSN: 1894-6402

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