Economic Analysis of Carbon Sequestration and Storage in Tanzanian Forests

Økonomisk analyse av karbonfangst og -lagring i tanzaniansk skog

Philosophiae Doctor (PhD) Thesis

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Summary

Tropical deforestation is among the principal causes of emissions of carbon dioxide (CO_2). Nevertheless, tropical forests play an important role in regulating global climate by serving as carbon reservoirs. This has led to the consideration of the policy measure known as REDD+ in the global climate change mitigation agenda. REDD+ stands for Reducing Emissions from Deforestation and Degradation, enhancing forest carbon stocks, sustainable management and conservation of forests. Assessing the economic feasibility of REDD+ policy is an important step towards implementing it. The objectives of this thesis were therefore to (1) estimate and compare the REDD+ payments required to compensate the opportunity costs (OCs) of stopping conversion of montane forest and miombo woodland into cropland (Paper I), (2) assess long-term productivity of agriculture on former miombo woodlands and its implication for OC estimation (Paper II), (3) investigate optimal use of miombo woodlands for charcoal production considering REDD+ payments for carbon sequestration and reduced degradation (Paper III), and (4) assess the past and future profitability of deforestation of miombo woodlands considering the externality of deforestation in terms of CO_2 emissions (Paper IV).

Data came from household surveys and focus group discussions (Papers I, II, III & IV), soil survey (Paper II), and various secondary sources (Papers I, II, III & IV). The study was conducted in the Morogoro region in Tanzania. REDD+ payment was estimated as the net present value (NPV) of agricultural rent plus forest revenue during land clearing, minus net returns from sustainable wood harvest, divided by the corresponding reduction in carbon stock (Paper I). In Paper II, a linear mixed-model and one way analysis of variance (ANOVA) were used to test the effect of permanent conversion of miombo woodland, and subsequent continuous cropping, on maize yield and selected soil properties, respectively. In Paper III, optimal solutions were determined based on four scenarios regarding payments for reduced degradation and rules related to changes in biomass density. The different scenarios were analyzed by running the model over a planning period of 30 years using nonlinear programming. Past (1964–2010) and future profitability of deforestation of miombo woodlands were examined using *Ex-post* and *Ex-ante* cost-benefit analysis (CBA), respectively (Paper IV).

The results showed that the OCs (USD ha^{-1}) of not clearing and cultivating the montane forest were similar to that of the miombo woodlands. However, the median required REDD+ payments to offset the OCs were significantly ($p < 0.001$) higher for the miombo woodlands (7–39 USD tCO_2e^{-1}) compared to the montane forests (1–3 USD tCO_2e^{-1}). This was mainly due to pronounced differences in carbon density between the two vegetation types. The findings suggest that avoiding deforestation of the montane forest would be feasible under the REDD+ scheme, given the possible factors that can potentially affect estimates of REDD+ payments. However, stopping deforestation of miombo woodlands would require a higher compensation level than the price found in current international contracts (5 USD tCO_2e^{-1}).

The results further indicated that clearing of miombo woodland and subsequent continuous cultivation did not lead to a significant decline in neither the most important soil nutrients nor in maize yield. This shows that the current farming system can maintain the major plant nutrients and thus productivity, although at a low level. This further implies that agricultural rent after deforestation of the miombo woodlands does not decline over time.

The economic optimal solutions for wood harvesting in miombo woodland were different for the different scenarios. Without payments for carbon sequestration and storage, at any discount rate above 7.3 %, immediate harvest of the current wood stock was the optimal solution. When payments were only made for increasing biomass (carbon) density, and when emission tax was considered for reducing biomass density (emissions of CO_2), the price of CO_2 required to stop wood harvest ranged from 10–30 USD tCO_2e^{-1}, depending on the price of charcoal and discount rate. When payments were made for both increasing biomass (carbon) density and reducing degradation, and when emission tax was also considered, for the current price of charcoal (5 USD/bag) and discount rates 5.3 % and 10 %, the CO_2 price had to be 10 and 15 USD tCO_2e^{-1}, respectively. If emissions were not taxed, however, a CO_2 price of 10–40 USD tCO_2e^{-1}, depending on the interest rates, would prevent wood harvest only until biomass density reached 100 t ha^{-1}. As in the case of stopping deforestation, stopping the degradation of miombo woodlands through REDD+, would require a high price of CO_2.

The results of the *Ex-post* and the *Ex-ante* CBA, showed that deforestation of miombo has been, and will continue to be profitable if the environmental costs of deforestation are not accounted for. However, fairly low prices of CO_2 would make deforestation unprofitable in the social analysis. At a discount rate of 10 %, this price was 8–11 USD tCO_2e^{-1} for the deforestation that took place since 1964 on the common land. At the same discount rate, CO_2 prices higher than 3.5–6 USD tCO_2e^{-1}, depending on the wage rates applied, would make potential deforestation of miombo woodlands in a forest reserve unprofitable. Incorporating other environmental costs of deforestation such as loss of biodiversity, could potentially reduce the profitability of deforestation further.

Sammendrag

Avskoging i tropene er en av de viktigste årsakene til menneskeskapte utslipp av CO_2. De tropiske skogene er viktige i klimasammenheng siden de fortsatt representerer store karbonlagre. Dette har medført at man har vurdert det klimapolitiske tiltaket som har fått betegnelsen REDD+ (Reducing Emissions from Deforestation and Degradation, enhancing forest carbon stocks, sustainable management and conservation of forests) i den internasjonale diskusjonen om global oppvarming. Å vurdere økonomien i dette tiltaket er et nødvendig skritt på veien til mulig gjennomføring. Målene med denne studien har derfor vært (1) å anslå og sammenligne de REDD+-betalingene som kreves for å kompensere de alternativkostnadene som følger av at man ikke kan rydde og dyrke opp fjellregnskog eller åpen lavlandsskog i Tanzania (artikkel I), (2) vurdere den langsiktige utviklingen i arealproduktivitet i åkerbruket etter oppdyrking av åpen lavlandsskog, og hvilken betydning dette har for alternativkostnadene (artikkel II), (3) undersøke optimal avvirkning i åpen lavlandsskog dersom man betaler for karbonlagring og redusert skogforringelse (artikkel III), og endelig (4) anslå lønnsomheten av historisk og framtidig avskoging av åpen lavlandsskog når man tar hensyn til kostnaden av CO_2-utslipp (artikkel IV).

Datamaterialet til denne studien ble samlet inn i spørreundersøkelser og fokusgruppe–diskusjoner (artikkel I, II, III og IV), jordprøver (artikkel II), og mange sekundære kilder (artikkel I, II, III og IV). Undersøkelsene ble gjort i Morogoro-regionen i Tanzania. REDD+-betalingene ble estimert som netto nåverdi av jorbruksproduksjonen pluss inntektene fra skogprodukter som blir tatt ut i forbindelse med oppdyrking, minus nettoinntektene fra utholdende virkeproduksjon i stående skog, dividert med den reduksjonen i karbonlagerene som følger av oppdyrkingen (artikkel I). En lineær mixed-modell og en enveis variansanalyse (ANOVA) ble brukt til å teste effektene av oppdyrking av åpen lavlandsskog og påfølgende permanent åkerbruk, både på avlingene av mais og på ulike næringsstoffer i jorden (artikkel II). I artikkel III ble optimal avvirkning til trekullproduksjon vurdert i forhold til fem alternative betalingsregimer for redusert skogforringelse og karbonlagring. Analysen ble gjort for en periode 30 år fram i tid. I artikkel IV ble det gjort en nytte-kostnadsanalyse av tidligere (1964–2010) og framtidig avskoging i åpen lavlandsskog.

Resultatene viser at alternativkostnadene per hektar av ikke å dyrke opp fjellregnskog og åpen lavlandsskog var relativt like (artikkel I). Ettersom det er betydelig forskjell på karbontettheten i de to skogtypene er den midlere (median) kompensasjonen som trengs per tonn CO_2e signifikant ($p<0{,}001$) høyere i åpen lavlandsskog (39 USD) enn i fjellregnskog (1 USD). Dette resultatet antyder at det å stoppe avskoging i fjellregnskogen i Tanzania kan være økonomisk gjennomførbart innenfor et REDD+-regime. Å stanse avskoging i åpen lavlandsskog vil kreve et høyere nivå på kompensasjonsutbetalingene enn det en finner i nåværende internasjonale avtaler (5 USD tCO_2e^{-1}).

Resultatene viser at oppdyrking av åpen lavlandsskog og påfølgende åkerbruk ikke førte til merkbar reduksjon av de viktigste næringsstoffene i jorden eller i maisavlingene. Dette indikerer at de dyrkingsmetodene som er i bruk i dag kan vedlikeholde næringsstoffer og dagens avlinger (som er ganske lave). Dette betyr videre at jordbruksinntektene etter avskoging ikke faller med tiden etter at skogen ble ryddet.

De økonomisk optimale løsningene for hogst av virke til trekullproduksjon i åpen lavlandsskog var forskjellige avhengig av betalingsregimene. Uten betaling for fangst og lagring av karbon var det optimalt å hogge all stående biomasse hvis rentekravet var høyere enn 7,3 % p.a. Hvis det ble betalt kun for akkumulasjon av biomasse i stående skog, og det ble krevd skatt for reduksjon av biomasse, ville en betaling på 10–30 USD tCO_2e^{-1} være nok for å gjøre slutt på hogsten – avhengig av rentekravet og prisen på trekull. Hvis det ble betalt for all nedgang i skogforringelse sammenlignet med dagens trend, og det ble krevd skatt for økt reduksjon av biomassen, ville en betaling på 10–15 USD tCO_2e^{-1} være tilstrekkelig. Om utslipp av CO_2 ikke ble skattlagt, ville priser på 10–40 tCO_2e^{-1} være nødvendige for å unngå hogst en periode, men når stående biomasse kom opp i om lag 100 t ha^{-1} ville skogen likevel bli avvirket. På samme måte som for avskoging i åpen lavlandsskog ville det også for skogforringelse være nødvendig med relativt høye priser på CO_2 i et vellykket REDD+-program.

Resultatene av *ex-post* og *ex-ante* nytte-kostnadsanalysene viste at avskoging av åpen lavlandsskog har vært, og vil fortsette å være, lønnsom hvis en ikke regner med miljøkostnadene som følger av klimagassutslipp eller redusert biomangfold. Relativt lave priser på utslipp av CO_2 gjør imidlertid slik avskoging ulønnsom i en samfunnsøkonomisk sammenheng. Ved et rentekrav på 10 % var denne prisen 8–11 USD tCO_2e^{-1} for avskoging som skjedde i allmenningen mellom 1964 og 2010. Ved samme rentekrav ville CO_2-priser på mer enn 3,5–6 USD tCO_2e^{-1}, avhengig av hvilket lønnsnivå en regnet med, gjøre framtidig oppdyrking av åpen lavlandsskog i reservater ulønnsom. Hvis en dessuten tar med tap av biologisk mangfold i regnestykket, er det sannsynlig at avskoging i slike områder vil være enda mer ulønnsomt.

List of papers

This thesis is based on the following four papers which are referred to by their roman numerals in the text (I-IV):

I. Araya M.M. & Hofstad O. (2014). Monetary incentives to avoid deforestation under the Reducing emissions from deforestation and degradation (REDD+) climate change mitigation scheme in Tanzania. *Mitigation and Adaptation Strategies for Global Change*. Published online: DOI: 10.1007/s11027-014-9607-y

II. Araya M.M (2015). Long-term responses of maize yield and selected soil properties to deforestation and subsequent cultivation of miombo woodlands in Tanzania. (*Manuscript*)

III. Hofstad O. & Araya M.M. (2015). Optimal wood harvest in miombo woodland considering REDD+ payments - a case study at Kitulangalo Forest Reserve, Tanzania. *Forest Policy and Economics*, **51**: 9-16.

IV. Araya M.M. & Hofstad O. (2014). Past and present profitability of deforestation of miombo woodlands considering CO_2 emissions in Maseyu village Tanzania. *Scandinavian Forest Economics*, **45**:182-190.

1 Background

1.1 Tropical forests and the global carbon cycle

Tropical forests are forests that grow in the tropics and encompass many vegetation types. These include: (1) *tropical humid or rain forests*: warm and wet forests occurring in the equatorial regions of the world where rainfall is abundant and the monthly average temperature is above 20 ^{o}C year round (FAO 2001); (2) *montane forests* also called *cloud forests*: forests that grow on tropical mountainsides (Hamilton et al. 1995); (3) *mangrove forests:* specialized tropical forests that grow near coasts at sites with extreme conditions such as high temperature, tidal flooding and boggy anaerobic soils (Giri et al. 2011); (4) *tropical dry forests*: forests occurring in the tropical regions where rainfall is seasonal, resulting in several months of drought (Bullock et al. 1995); and (5) *Savannahs (woodlands)*: forests found under similar climatic conditions as the tropical dry forests, but on relatively poor soils (Sarmiento 1992).

Tropical forests cover about 7 % of the World's total land area (Allaby 2006) and provide various ecosystem services. They contain about 50 % of the World's surface terrestrial biological diversity (Mayaux et al. 2005). They are also home to over two hundred million humans (Scrieciu 2007) and about 1.6 billion people depend directly on tropical forests for food, fiber, fodder, fuel and other resources (World Bank 2004). Furthermore, tropical forests play an important role in regulating global climate by serving as carbon reservoirs. Currently these forests are believed to store about 228.7 petagram (Pg) of carbon (Baccini et al. 2012).

Forests in general play an important role in the global carbon cycle. They can either be a source of atmospheric carbon in the case of biomass combustion, or a sink in the case of carbon sequestration from growth. The global forest pool has been estimated to contain about 80 % of the aboveground, and 40 % of the belowground carbon stored in terrestrial ecosystems (Dixon et al. 1994). About 43 % of global forests are found in the tropics, of which 42 % are located in arid and semi-arid areas (dry forests, woodlands and rangelands) (Brown et al. 2005, Glenday 2008). In general, dry forests have lower biomass stocks than wetter forests. However, the more widespread coverage of dry forests make them a considerable terrestrial carbon store (Glenday 2008). The net carbon budget of a forest is the difference between the amount of carbon gained through processes such as photosynthesis, tree growth and soil carbon sequestration, and the amount of carbon released to the atmosphere through processes such as respiration of living plants, tree mortality, microbial decomposition of litter, soil carbon oxidation, and biomass combustion. The tropical forest biome is generally considered as a net source of CO_2 to the atmosphere as compared to mid- and high latitude forests (Brown et al. 2005). During the period between 1990 and 2009, average annual net emissions of carbon from tropical deforestation are estimated to be about 1.4 ± 0.5 Pg (Houghton 2012). Baccini et al. (2012) also showed that, over the period between 2000 and 2010, total net emission of carbon from tropical deforestation and land use was estimated to be 1 Pg per year.

1.2 Tropical deforestation and degradation

Deforestation refers to long term or permanent conversion of forest cover to another land use, while degradation is a reduction of canopy cover or biomass density within a forest (FAO 2007, Houghton 2012). Despite the wide range of goods and services they provide, tropical forests of all kinds have been declining at an increasingly rapid rate, although there are now some signs indicating a reduction of the current deforestation rate (FAO 2010). Nearly half of the original tropical forests have already been lost (Wright 2005). In the 1990s, an estimated area of 5.8 and 2.3 million ha of humid tropical forests were deforested and degraded annually, respectively. During the same period, tropical moist deciduous and tropical dry forests were declining at an estimated rate of 2.2 and 0.7 million ha per year, respectively (Mayaux et al. 2005). Between 2000 and 2005 the annual deforestation rate across tropical countries was approximately 6.3 million hectares per annum, with the highest rate in the dry tropics (Harris et al. 2012). Tropical deforestation is the second largest source of carbon dioxide (CO_2) to the atmosphere. During the years between 2000 and 2005, it accounted for 7 to 14 % of global human-induced CO_2 emissions (Harris et al. 2012). It is also a major cause for loss of biodiversity (Lugo et al. 1993).

Various theories have been formulated to explain the driving forces of tropical deforestation. Geist and Lambin (2002) have identified four major proximate (direct) and five major underlying (indirect) causes. Proximate causes are human activities at local level that have a direct impact on forest cover, while underlying causes are fundamental forces that underpin the proximate causes (local actions) directly at the local level or indirectly from the national or global level. The proximate factors include: infrastructure extension (transport, markets, settlements, public service and private company); agricultural expansion (permanent cultivation for both subsistence and commercial purposes, shifting cultivation, cattle ranching and colonization); wood extraction (commercial, fuelwood and polewood mainly for domestic purposes, and charcoal production for both domestic and commercial uses); and other factors (pre-disposing environmental factors such as soil quality and topography, biophysical drivers such as fires and pests, and social trigger events such as war and abrupt displacements). Factors grouped as underlying causes are: demographic factors (natural increment, migration, population density, population distribution and life cycle futures); economic factors (market growth and commercialization, economic structures, urbanization and industrialization, and special variables such as price increases and comparative cost advantage); technological factors (agro-technical change, applications in the wood sector and agricultural production factors); policy and institutional factors (formal policies, policy climate and property rights); cultural factors (public attitudes, values and beliefs, and individual and household behavior).

Proximate drivers of deforestation and degradation vary across regions and among countries. Conversion of tropical forest to pasture and cattle ranching by both small and large producers are major causes of deforestation in Latin America, particularly in the Brazilian Amazon (Walker et al. 2000) and in the Colombian Amazon (Armenteras et al. 2006). In South East Asia, particularly in Indonesia and Malaysia, commercial logging and oil palm plantations are the major causes of rainforest destruction (Palmer 2001, Koh and Wilcove 2008, Koh et al. 2011). In Africa, both permanent and shifting agriculture is the main driver of deforestation (Kissinger and Herold 2012). In general, agricultural expansion for both commercial and subsistence usages remains the most important proximate cause of tropical deforestation. Worldwide, it is responsible for the removal of 13 million hectares of forest per year, accounting for about 80 % of all deforestation (Hosonuma et al. 2012, Kissinger and Herold 2012). Commercial agriculture (including livestock) contributes to around 68 % of deforestation in Latin America and 35 % in each Africa and Asia, while subsistence agriculture accounts for 27–40 % of deforestation in each of these continents (Hosonuma et al. 2012). The main drivers of forest degradation in Latin America and Asia are commercial timber extraction and selective logging, accounting for more than 70 % of the deforestation. In Africa, fuel wood collection and charcoal production are the main forest degrading factors (Kissinger and Herold 2012).

1.3 Status of Tanzanian forests and woodlands

Tanzania possesses an estimated 48 million ha of forests and woodlands, covering about 51 % of the country's total land area (NAFORMA 2014). About 93 % of the forested and wooded area is made up of miombo woodlands (NAFORMA 2014). Miombo, a collective name for woodlands dominated by species of the genera *Brachystegia*, *Julbernardia*, and *Isoberlinia*, is a common vegetation type also in Angola, Zimbabwe, Zambia, Malawi, Mozambique and the southern part of the Democratic Republic of Congo (

Figure 1). The miombo area covers an estimated 2.4 million km^2 and supports the livelihoods of about 75 million rural and 25 million urban people (Dewees et al. 2010). The woodlands provide a wide range of goods and services, of which fuelwood is the most important for the urban population (Campbell 1996). The woodlands generally occur on nutrient-poor soils in areas that receive 650–1400 mm of annual rainfall. In general, the soils have low contents of N and extractable P (Frost 1996). Other vegetation types include montane forests of the Eastern Arc mountains (EAM), mangrove forests, acacia savannah, and coastal forests (Burgess et al. 2010). The EAM is a chain of mountains stretching from the Taita Hills in southern Kenya through eastern Tanzania to the Udzungwa Mountains of south-central Tanzania (

Figure 1). It consists of 13 distinct mountain blocks; Taita, North Pare, South Pare, West Usambara, East Usambara, Nguu, Nguru, Uluguru, Ukaguru, Rubeho, Malundwe, Udzungwa and Mahenge (Burgess et al. 2007). The 13 blocks of the EAM support an estimated 3300 km^2 of sub-montane (below 1,500 m a.s.l.), montane (1,600–2,400 m a.s.l), and upper montane (above 2,400 m a.s.l) forests (Burgess et al. 2007, FBD 2009). The EAM is known for its high concentrations of endemic species of vertebrate animals (96 species) and vascular plants (800 species) (Burgess et al. 2007).

About 52 % of the forests and woodlands in Tanzania are within protected areas, and the remaining percentage is on village or general (*de facto* open access) lands (Zahabu et al. 2007, Mbwambo et al. 2012). Tanzania is one of many countries currently experiencing a high rate of deforestation. It has been estimated that the country has lost an average of 400,000 ha (about 1 %) of its forests and woodlands per year during the period 1984–2010 (NAFORMA 2014). Agricultural expansion has been identified as one of the main drivers of deforestation in Tanzania (Makundi and Okiting'ati 1995, Angelsen 1999, Luoga et al. 2005, Kissinger and

Herold 2012). In addition, particularly the miombo woodlands have been subject to extensive extraction of wood for charcoal making (Monela et al. 1993, Luoga et al. 2005, Nduwamungu et al. 2008).

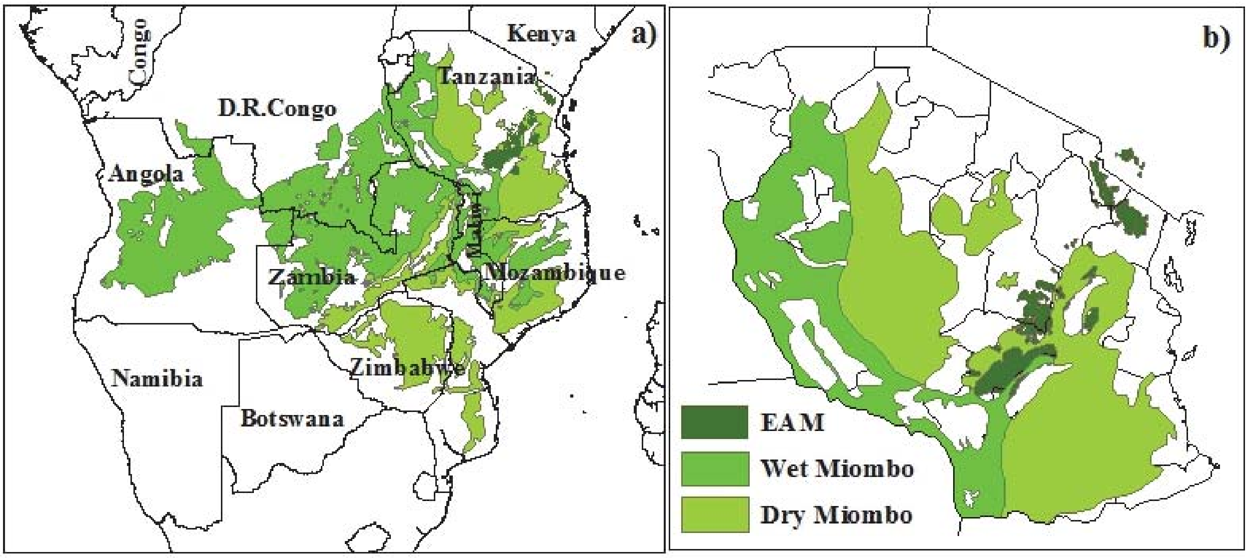

Figure 1. Distribution of miombo woodlands, and the Eastern Arc mountains (EAM) in Africa (a) and in Tanzania (b). The source of the shape files was Frank (1983) and Platts et al. (2011).

1.4 Forest-based climate change mitigation measures

The significance of forests, particularly tropical forests, in the global carbon cycle has led to the consideration of forest-based climate change mitigation measures in the international climate negotiations, agreements and policy frameworks. The United Nations Framework Convention on Climate Change (UNFCCC), with the Kyoto Protocol (KP), is an agreement which aims at reducing atmospheric CO_2 emissions through the provision of a market for carbon trading (UNFCCC 1998). It recognized the role of forestry as a potential means to reduce the build-up of atmospheric CO_2. The first forest-based climate change mitigation measure, “Afforestation/Reforestation”, was included in the KP framework trough the “Clean Development Mechanism” (CDM) to be implemented during the initial commitment period of 2008 through 2012. The CDM Afforestation/Reforestation (CDM-AR), as defined by Article 12 of the UNFCCC’s KP, aimed at mitigating emissions of CO_2 while helping developing countries in achieving sustainable development (UNFCCC 1998). Parties to the UNFCCC with the KP further developed a mechanism for reducing emissions from deforestation and forest degradation, enhancing forest carbon stocks, sustainable management and conservation of forests (REDD+) in developing countries to be implemented in the post-2012 commitment period (UNFCCC 2010).

The compensation-based policy mechanism originally described as RED (Reducing Emissions from Deforestation) was initially introduced into the international climate negotiations in 2005 as a way to combat deforestation, and thus reduce carbon emissions (Wertz-Kanounnikoff and Kongphan-apirak 2009). RED was then expanded to also include the reduction and prevention of forest degradation, and consequently became REDD (Reducing Emissions from Deforestation and Degradation). REDD was included in the international climate negotiations in 2007 at the UNFCCC 13th conference of the parties (COP) in Bali (Wertz-Kanounnikoff and Kongphan-apirak 2009). In 2008 at the COP-14 in Poznań, it became REDD+, thus to include the possibility of offsetting carbon emissions through forest conservation, sustainable management of forests and the enhancement of forest carbon stocks, and also to incorporate co-benefits of forest protection (Angelsen and Wertz-Kanounnikoff 2008, Bosetti and Rose 2011, Angelsen et al. 2012b). Under this scheme, landowners/users, communities and governments in tropical developing countries that are willing and able to reduce forest carbon emissions and/or to enhance forest carbon stocks, would be rewarded financially for their achievements in doing so.

1.4.1 Potential costs of REDD+

There are three major costs associated with the implementation of this policy: opportunity costs, implementation costs, and transaction costs.

Opportunity costs (OCs) are the net benefits that will be forgone by preventing conversion of forest land to other land-uses (deforestation) or preventing harvesting of timber, wood for charcoal and other products in ways that degrade forests (forest degradation), through implementing a REDD+ program. These costs could be incurred by the national government, by local communities, or by individuals. Most REDD+ OC estimates are estimated from the perspective of a private forest owner or user, that is, the foregone net benefits from the best alternative land use options (Angelsen et al. 2012a). These costs can be seen as payments required to compensate forest owners or users for their forgone benefits (Angelsen 2008). REDD+ payments to offset OCs can be estimated as the net present value (NPV) of the next best use of forest land, divided by the associated reduction in carbon stock (Wertz-Kanounnikoff 2008). In addition to the forgone economic benefits from the alternative land use, i.e. direct (on-site) costs, OCs also comprise socio-cultural and indirect (offsite) costs (White et al. 2011). Socio-cultural OCs of not deforesting or degrading forests are costs such as psychological, spiritual or emotional impacts of livelihood change, loss of local knowledge, and erosion of social capital. These costs are difficult to measure in monetary terms and can be reduced by providing alternative livelihoods along with the implementation of a REDD+ program. Indirect costs of reducing conversion of forest land to mainly agriculture include changes in land use and economic activities, and thereby increased costs of food and fuel. Such costs can be estimated using multi-market models.

Implementation costs are costs related to activities aimed at directly stopping or reducing drivers of deforestation and forest degradation, or enhancing forest carbon stocks. These include land use planning, land tenure/governance reform, forest protection, reforestation and restoration, improved forest and agriculture management, capacity building, job training and administration (White et al. 2011). Another category of costs associated with implementation of REDD+ is that of institutional costs. These are costs that are taken on at the national level of government administration and are associated with the development, management and enforcement of REDD+ policy. These costs could be related to legal, governance, or enforcement actions taken by the administration to carry out the management and enforcement of REDD+ policy.

Transaction costs are costs related to establishing and running of the program (Wertz-Kanounnikoff 2008). These are costs necessary for REDD+ program identification, transaction negotiation (by the buyer and seller, or donor and recipient), and monitoring, reporting and verifying the emissions reductions (White et al. 2011). These costs are incurred by implementers of the REDD+ program and third parties such as verifiers, certifiers, and lawyers. The difference between implementation and transaction costs is that the later do not avoid or reduce deforestation or forest degradation by themselves. Figure 2 illustrates different transactions in a hypothetical REDD+ system among global carbon markets and funding organizations, states, communities, individuals, and others.

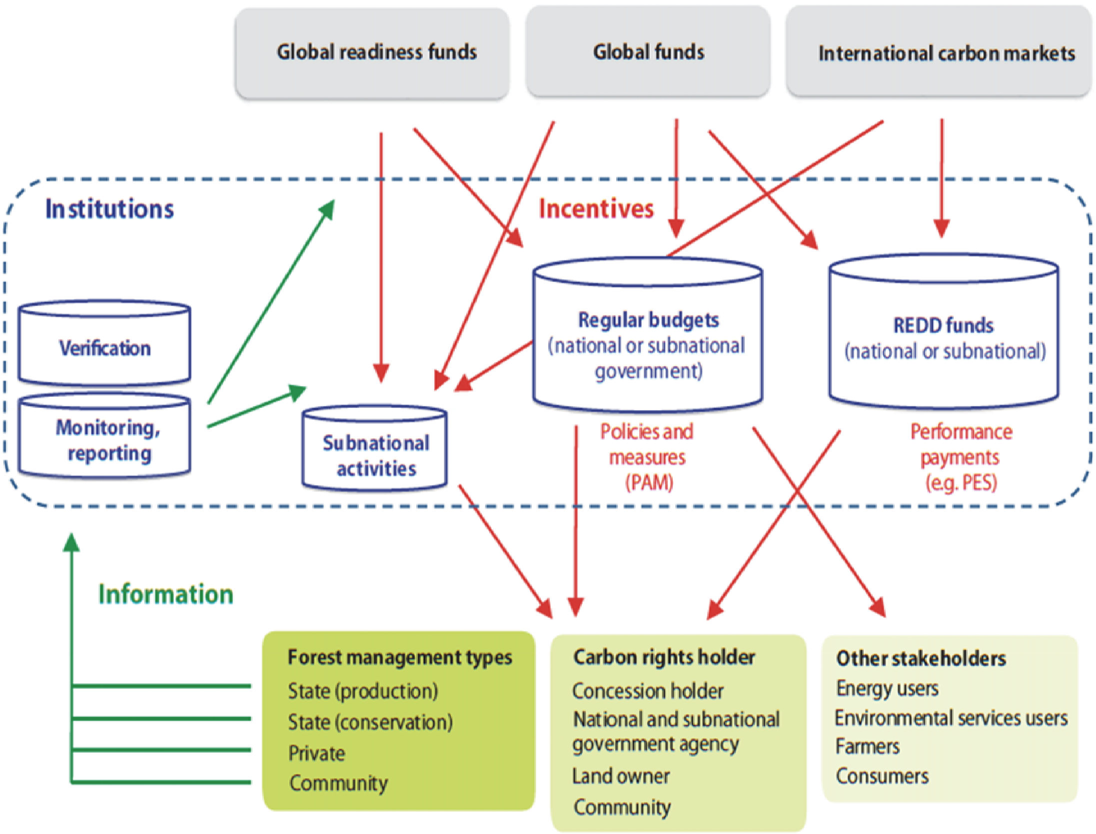

Figure 2. Transactions between different stakeholders in a hypothetical REDD+ system (Source: Wertz-Kanounnikoff and Angelsen (2009)).

1.4.2 Economic models used for the analysis of REDD+

Approaches to analyzing economics of REDD+ can be broadly categorized into local (empirical) and global (empirical or simulation) models (Boucher 2008). Local models are spatially detailed models. Their estimates regarding both returns to land uses and carbon density per unit area are based on information which is specific to a particular area. Estimates of global models, on the other hand, are either aggregated local estimates to a global scale or simulated estimates on a global basis. Based on economic scope, resolution (spatial, sectorial and temporal) and market endogeneity, four types of REDD+ economic models can be identified in the literature. These are fixed market, partial equilibrium, general equilibrium, and integrated assessment models (Lubowski and Rose 2013).

Fixed market models are site specific models with a relatively narrow temporal and economic scope and consequently can assume exogenous market conditions, i.e. they do not consider changes in output and input prices or changes in climate. Partial equilibrium models have a wider spatial, temporal and economic range compared to fixed market models. They include changes in forest and agricultural product prices and their effect on the national and international demand for the products. These models are used for estimation of potential national, regional and global supply curves for emissions reductions from deforestation and degradation. General equilibrium models have narrower temporal range, but wider economic scope, compared to partial equilibrium models. Integrated assessment models are the most complete economic models, with a wide economic, spatial and temporal scope. They assume endogenous market conditions, i.e. they consider changes in both output and input prices, as well as climate.

1.5 Rationale of the study

Tropical deforestation and consequent emissions of CO_2, loss of biodiversity and other important ecosystem services, have become issues of global environmental concern. This led policy makers, scientists and the public to increase efforts to reduce deforestation and degradation of tropical forests. Recognition of the REDD+ policy in the climate change mitigation agenda is among the efforts towards reducing or stopping deforestation and degradation of forests in tropical developing countries. REDD+ is widely recognized as a relatively cost effective way to achieve emissions reductions, which is one of the main rationales for including the policy measure in the global climate agreement. It is also believed that REDD+ is an opportunity to achieve multiple objectives such as biodiversity conservation and sustainable development. As with many environmental policies, there are costs and benefits, as well as opportunities and risks, associated with the implementation of this policy. The overall effectiveness and feasibility of the policy depends on a number of ecological and economic factors, which are crucial to identify and analyze in order to inform decisions on where to establish projects.

2 Objectives and research questions

The general objective of this study was to investigate economic feasibility of carbon sequestration and storage in Tanzanian forests under the REDD+ scheme. The specific objectives were to:

1. Estimate and compare REDD+ payments required to compensate the OCs of stopping deforestation of montane forests and miombo woodlands (Paper I). Research questions addressed are:
    a. What are the compensation payments to local farming households required to stop the conversion of montane forests and miombo woodlands into cropland?
    b. What is the effect of varying assumptions in factors such as wage rate on the OC estimates, and thus on the level of required REDD+ payments?
2. Assess long-term productivity of agriculture on former miombo woodland and its implication for OC estimation (Paper II). Research questions addressed are:
    a. What is the effect of clearing and subsequent continuous cultivation of miombo woodlands on the yield of maize, and the physical and chemical properties of the soil?
    b. What are the implications of the results for OC estimation?
3. Investigate optimal wood harvest in miombo woodlands considering REDD+ payments for carbon sequestration and reduced degradation (Paper III). Research questions addressed are:
    a. How high REDD+ payments are required to compensate the OCs of stopping degradation of miombo woodlands?
    b. What are the important factors determining optimal wood harvest in miombo woodlands?
4. Assess past and future profitability of deforestation of miombo woodlands (Paper IV). Research questions addressed are:
    a. Has deforestation of miombo woodlands been profitable even when considering the externality of CO_2 emissions?
    b. Can further deforestation of relatively intact miombo woodlands be profitable if payments for carbon sequestration and tax for carbon emissions are considered?

3 Materials and Methods

3.1 Study sites

The study was conducted in seven villages in Morogoro Region in Tanzania: Kunke, Maseyu, Mlimbilo, Ng'ungulu, Nyandira, Tchenzema, and Vinile (Figure 3). The first three are located at an average altitude of 400 m.a.s.l., hereafter referred to as the lowland zone. The remaining four villages are located between 1,000 and 2,700 m.a.s.l., hereafter referred to as the highland zone. The two agro-ecological zones comprise two distinct vegetation types: miombo woodlands in the lowland zone and montane forest in the highland zone.

The villages of Kunke and Mlimbilo are located in Mtibwa Ward, 120 km north of Morogoro town while Maseyu is located in Gwata Ward, 50 km east of Morogoro town along the Dar es Salaam-Morogoro highway (Figure 3). According to the local administration offices, the villages cover an area of about 24,000 ha, 13,600 ha and 36,000 ha, and have about 3,500, 2,000 and 2,000 inhabitants, respectively. The climate of the zone is sub-humid tropical, with mean annual rainfall ranging from 800 to 1,200 mm (MRDO 2006). The rainfall has a bimodal distribution with the short rains extending from October to December, while the long rainy season occurs between March and June. The mean annual temperature varies between 28 and 31°C (MRDO 2006). The vegetation type is generally characterized as open, dry miombo woodland. The villages include settlements, croplands, open miombo woodlands, village forest reserves and parts of a protected miombo woodland known as the Wami-Mbiki wild animals' management area (WMA). In addition, Kunke includes a sugar factory and teak plantations, Kunke and Mlimbilo include sugarcane plantations while Maseyu comprises part of the Kitulangalo Forest Reserve (KFR) (about 70 % of it). The inhabitants of the zone depend mainly on agriculture for their livelihoods. They are small-scale farmers cultivating crops for subsistence (maize) and for the market (rice, sesame, and sugarcane). The local people are highly dependent on forest resources from both protected and unprotected woodlands, both for their own consumption (firewood, fruit and vegetables, and wood for poles) and for commercial purposes (charcoal). The WMA is a community-based conservation area that was established in 1999. The area covers approximately 4,200 km^2 and is surrounded by 24 villages including the three study villages (Madulu 2005). The WMA covers 65 % of Kunke, 47 % of Mlimbilo, and 73 % of Maseyu villages. The woodlands inside the WMA have been suffering from extensive tree cutting for charcoal production, and agricultural expansion and encroachment.

The KFR was first gazetted in 1955 (GN198 of 3/6/1955) (Malimbwi and Mugasha 2001) and established as a 'productive reserve' in 1985, with the aim of controlled utilization of the woodland. In 1995 however, the reserve was closed for all kinds of uses (Luoga et al. 2002). The reserve covers about 2,452 ha, including the semi-evergreen forests in the Kitulangalo hills (Luoga et al. 2004). The part of the forest reserve located in Maseyu is managed jointly by the central government and the village. The current management system has been practiced since 2000. The reserve is formally protected, but in practice tree cutting is common and there have been some cases of conversion into crop land. An estimated 1.2 m^3 ha^{-1} of wood is illegally harvested from the reserve annually (Luoga et al. 2002). Moreover, in the period 1975–2000, closed woodland in the reserve and the surrounding area declined by 45 %, while open woodland in the surrounding area increased by 42 % (Nduwamungu et al. 2008). It has been suggested that REDD+ monetary incentives may help to reduce the problem of deforestation and forest degradation of these woodlands (Zahabu et al. 2007).

The villages Ng'ungulu, Nyandira, Tchenzema, and Vinile are located in Mgeta Division, about 200 km west of Dar es Salaam (Figure 3). The climate in the area is tropical, with an average annual rainfall in the range of 1,000–2,000 mm. The rainy season lasts from November to May. The mean annual temperature varies from 15 °C to 21 °C (Kapilima 1992). The surrounding farmlands extend up to the border of the Uluguru Nature Reserve (UNR). The inhabitants in adjacent areas to the UNR practice intensive small-scale farming of both subsistence crops (maize and pulses) and cash crops (vegetables), and rely mainly on family members for labor. The UNR, which is part of the EAM, covers an area of approximately 240 km^2 and is surrounded by 57 densely populated villages. Rivers originating in the reserve are the main supply of water to the local communities, as well as to Morogoro town and Dar es Salaam (Lundgren 1978). The UNR is one of the world's biodiversity hotspots (Poynton et al. 2007). It also plays an important role as a carbon reservoir, currently storing about 10.3 million tons of carbon (FBD 2010). The reserve, which is managed by the central government, has been protected since the 1910s, was gazetted in 1950, and the cutting of trees has since been officially prohibited. However, illegal harvesting of wood from the reserve has continued. Moreover, between 1955 and 2000, 25 % of the forest was lost, mainly due to agricultural expansion (Burgess et al. 2002). To mitigate this, the government allowed households in the surrounding villages to collect firewood, fruits, herbs, and other non-wood forest products for their own consumption (FBD 2009). The UNR comprises four separate forest reserves:

Uluguru North, Uluguru South, Bunduki, and Bunduki Gap. Our study was conducted on the southwestern side of the Uluguru Mountains, next to the Uluguru South forest reserve (USNR).

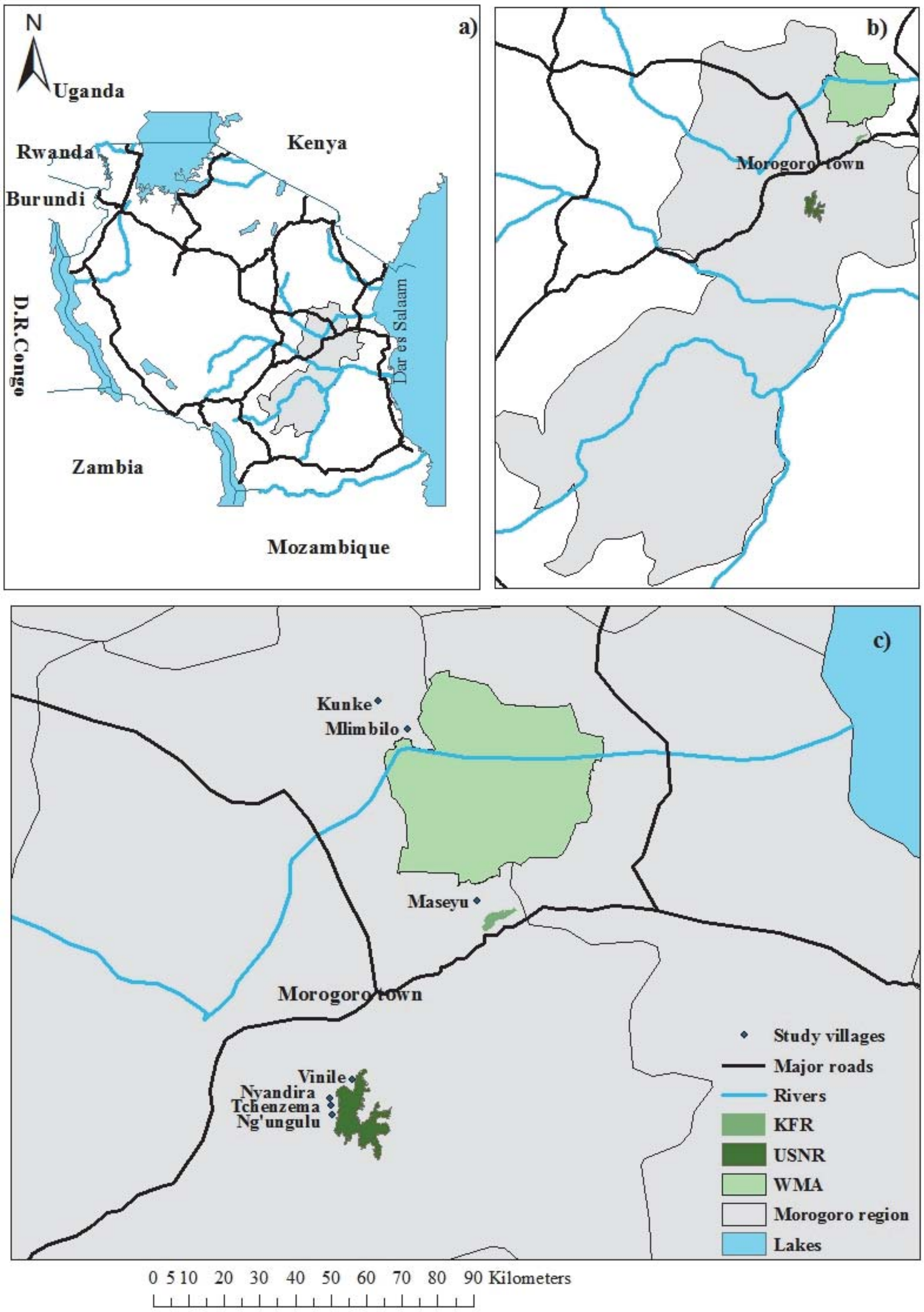

Figure 3. Map of the study area, Tanzania (a), Morogoro region (b) and study villages (c).

3.2 Data and soil samples collection

3.2.1 Household survey (Papers I, II, III & IV)

The household survey was conducted in the seven study villages. A total of 112 households were randomly selected from the four villages in the highland zone, and 119 from the three villages in the lowland zone. Basic demographic information, data on characteristics of farming plots, crop production, forest resource use, as well as information relating to costs and revenues associated with crop production and forestry activities, local prices of all inputs and outputs, and cost of labor, were obtained using structured questionnaires. Additional information was collected through focus group discussions.

3.2.2 Secondary data (Papers I, II, III & IV)

The types of information gathered from various secondary sources include: stand volume (m^3 ha^{-1}) and density (No ha^{-1}) of miombo woodlands in KFR and on the surrounding public land, and of montane forest; economic parameters and conversion factors such as log and timber recovery used to estimate forest revenue during land conversion as well as from a sustainable harvest; current aboveground woody biomass density (t ha^{-1}) of miombo woodlands in KFR and on the surrounding public land; tree diameter at breast height (DBH) and height (H) measurements from permanent sample plots in KFR; carbon stock (t ha^{-1}) in different pools of miombo woodlands, montane forest and the surrounding crop lands; deforestation rate and deforestation history (land use and land cover change since 1964) in Maseyu village; the last population censuses (2002) and population growth rate; lending interest rate by the bank of Tanzania as of January 2011 and inflation rate of all items for the period January 2010 to January 2011; and statistics (1964-2011) of current (nominal) local (farm-gate in Maseyu village) and global (USA) price of maize, local (in Maseyu village) price of charcoal, exchange rates and consumer price index.

3.2.3 Soil survey (Paper II)

Data on some soil properties were required to achieve the objective of Paper II. Hence, a soil survey was undertaken in Maseyu village. Composite soil samples at two depths (0–10 cm and 11–20 cm) were collected from twelve closely located farmlands and from three plots in the adjacent miombo woodland in the forest reserve. Another set of soil samples for bulk density determination were collected using a core sampler from each plot.

4 Data and soil analysis

4.1 Economic analysis

In Papers I & IV, a CBA was used to estimate the OC of not converting forestland into crop land, and to assess profitability of deforestation and maintaining the woodlands in KFR, respectively. CBA involves identification, quantification and valuation of benefits and costs. Accordingly, all benefits and costs to local farming households associated with deforestation and subsequent cultivation (Papers I & IV), and maintaining the woodlands in KFR (Paper IV), were identified, quantified and valued. The benefit items of deforestation (conversion of forestland into cropland) are crop produce and wood obtained during land conversion. Deforestation also involves cost of land clearing. Environmental cost of deforestation in terms of CO_2 emissions is also considered in Paper IV. The costs of crop production included the cost of seeds, fertilizers, pesticides and fungicides, labor required for different activities, and transportation to the local market. Wood obtained during clearing is assumed to be used for charcoal production in the lowland zone and for poles, timber and tool handles in the highland zone. Charcoal production requires labor (mainly family members) for different activities such as felling and cross-cutting of trees, log piling, stacking, and loading and unloading charcoal kilns. Similarly, the production of logs and timber requires labor (mainly hired) for different activities. The costs and benefits were valued using local market prices. With regard to valuing a farmer's own labor, we applied and compared three different wage rates: (1) the reported wage rate in the study villages (hereafter referred to as the "village wage rate"), (2) the minimum wage rate for agricultural labor in Tanzania ("minimum wage rate"), and (3) a wage rate equal to zero ("zero wage rate"), which assumed an opportunity cost of labor as zero. The cost-benefit flows were discounted to provide an estimate of the NPVs of clearing and cropping as well as maintaining the protected woodland in KFR. Sensitivity of results to changes in some of the key parameters (discount rate, cost of labor, carbon density, and crop yield) was analyzed.

4.2 Growth model development

Investigation of optimal use of the miombo woodlands in KFR (Paper III) as well as estimation of carbon sequestration rate by the woodland in KFR (Paper IV) required an estimate of the growth rate of the vegetation. Therefore, we developed a simple growth model, based on the Verhulst equation (Verhulst 1838), to describe the development of biomass of the woodland. Data on H and DBH obtained from permanent plots in KFR (Ek 1994) and an allometric function, $S = 0.06\ DBH^{2.012}\ H^{0.7}$ (Malimbwi et al. 1994), were used to estimate biomass. The Verhulst equation relates the stock, S, and the increment, $\dot{S}$, of biomass in the woodland: $\dot{S} = a S - b S^2$, where a and b are positive constants. The constants a and b were estimated by fitting a linear regression model. We used fitted versus residual plot (a constant variance test) to evaluate the model. Biomass reductions due to fire and illegal wood harvest are incorporated in the model. Illegal harvest and fire were assumed to be constants in all future.

4.3 Optimization

Optimization was done at a stand level (KFR) with the objective function of maximizing the NPV of charcoal production and payments for carbon sequestration and reduced degradation. Optimal solutions were determined based on the following four scenarios regarding payments for reduced degradation and rules related to changes (increase/reduction) in biomass density, and thus to carbon sequestration and storage, or CO_2 emissions. Three of the scenarios are illustrated in Figure 4.

1. There will not be payments for carbon sequestration and/or storage
2. Payments will be made for increasing biomass density but not for reduced degradation, and there will be a punishment for biomass reduction (a tax equal to the CO_2 price)
3. Payments will be made for increasing biomass density as well as reduced baseline degradation (4.3 % of biomass in the previous year), and there will be a punishment for biomass reduction above the baseline
4. Payments will be made for increasing biomass density as well as reduced baseline degradation (4.3 % of biomass in the previous year), and there will not be a punishment for biomass reduction

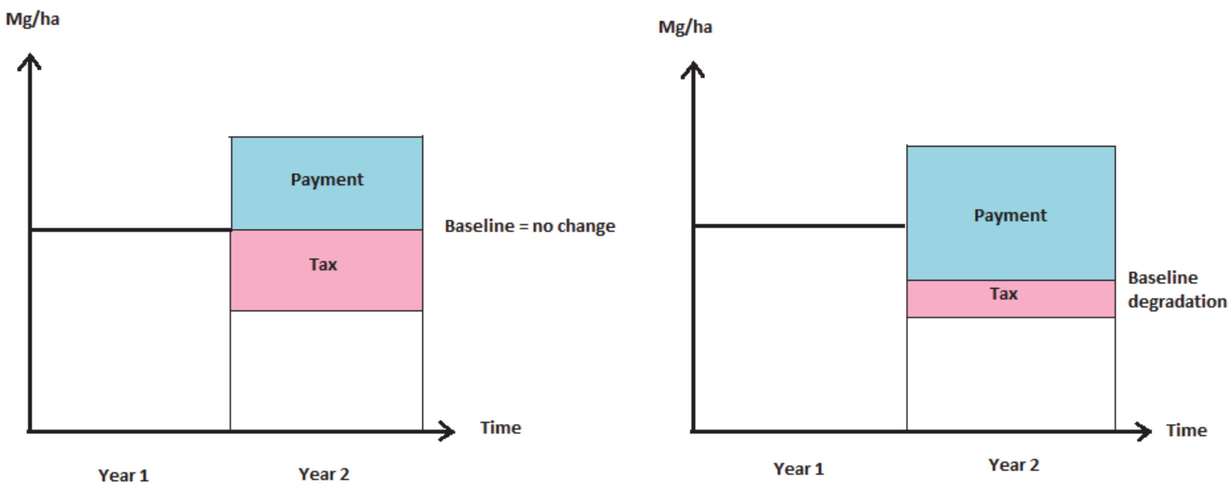

Figure 4. Three of the four scenarios regarding payments for reduced degradation and rules related to changes in biomass density. Scenario two (left) and scenarios three and four (right).

The different scenarios were analyzed by running the model over a planning period of 30 years, using nonlinear programming using the solver algorithm for the Microsoft Excel spreadsheet. The model was run with different values for prices of charcoal and carbon, and for different discount rates.

4.4 Soil analysis

Analyses of soil physical and chemical parameters were undertaken at the Sokoine University of Agriculture in Morogoro, Tanzania. Soil pH was measured in a 1: 2.5 mixture of soil: water using a pH electrode. Organic carbon was determined by the wet oxidation method of Walkley and Black (Nelson and Sommers 1982) and converted to organic matter by multiplying by a factor of 1.724. Total nitrogen was determined using the Kjeldahl method (Bremner and Mulvaney 1982). Available phosphorus was extracted by the Bray and Kurtz-1 method (Bray and Kurtz 1945) and it was determined using a spectrophotometer (Murphy and Riley 1962, Watanabe and Olsen 1965). Exchangeable potassium was extracted by saturating soil with neutral 1M NH4OAc (Thomas 1982) at a pH of 7.0, and the extracted potassium was measured by an atomic absorption spectrophotometer. Texture was determined in soil suspension by a hydrometer method (Day 1965). Bulk density was determined using the core sample method (Blake 1965).

4.5 Statistical analysis

4.5.1 Socioeconomic data

Before analysis, the data were subjected to a normality test. In Paper I, a Kruskal-Wallis test was used to detect statistically significant differences in the median NPVs of crop production as well as the median REDD+ payment estimates between the two agro-ecological zones and among the study villages within the zones. Non-parametric multiple pair-wise comparisons between different parameters were made using Tukey's test and t-tests, with a significance level of $\alpha = 0.05$. In Paper II, a linear mixed model was applied to examine the effect of the important variable, cultivation period (age of a given plot) and other factors (explanatory variables) which were thought to have both fixed and random effects on maize yield. Before analysis, the explanatory variables were tested for correlation between each other. Furthermore, a test for lack of fit was made in order to check if the model fitted the data. In both Papers I and II, the statistical software R version 3.0.1. (R Core Team 2013) was used for analysis.

4.5.2 Soil data

The cultivation period (age) of the plots was categorized into five groups and ANOVA was used to detect statistically significant differences in mean value of each soil parameter per depth among the different categories of cultivation periods. Pair-wise comparisons of means of each soil parameter per depth between the different cultivation period groups were made using Tukey's studentized test. A significance level of $\alpha = 0.05$ was used. Soil organic C stock (SOC) (g m^{-2}) was calculated using the formula SOC = SOC * BD * D * 100, where SOC is the carbon stock in g m^{-2} of a sample depth, D is the depth of a sample layer (cm), BD is the bulk density in g m^{-3} of a sample depth D, and SOC id the carbon content in g $100g^{-1}$ soil of a sample depth. The same equation was applied to estimate the stock of Total N (g m^{-2}) for each soil layer.

5 Main Results

5.1 Required REDD+ payments to offset OCs of stopping deforestation

At a 5.3 % discount rate, the median OC (USD ha^{-1}) of not converting forestland into cropland ranged from 1,482 to 4,660 in the highland villages. In the lowland villages, it was in the range of 1,289–4,932 and 1,363–5,006, depending on the biomass density of the woodland to be converted. The OC estimates were in a similar range in both agro-ecological zones. The median required price of CO_2, to offset these OCs were however, significantly higher ($p < 0.001$) for the villages in the lowland zone compared to the villages in the highland zone. It ranged from 10–39 USD tCO_2e^{-1} and 7–25 USD tCO_2e^{-1} to protect the current carbon stocks in degraded and relatively intact miombo woodlands, respectively, and 1–3 USD tCO_2e^{-1} in the montane forest. The estimates were significantly higher when the cost of farmers' own labor was not taken into account in NPV calculations. In contrast, the estimates decreased significantly when the discount rate was increased to 10 %. The variation in the required REDD+ payments between the two agro-ecological zones were due to the pronounced differences in biomass (carbon) density between the two vegetation types. The variation between villages in the same agro-ecological zone was, however, due to the choice of crop types attributed to both agro-ecological conditions and market access. Regarding forest use rules that will be applied following the implementation of the REDD+ policy, this analysis assumed that wood harvesting would continue in a sustainable way. Sustainable wood harvest in this case was defined as a harvest less or equal to the mean annual increment of the forest or woodland under consideration. The results revealed that depending on the wage rates used, sustainable annual wood harvest could offset up to 45 % and 55 % of the estimated total median OCs of protecting the miombo woodlands and the montane forest, respectively.

5.2 Long-term productivity of agriculture on former miombo woodlands and its implication for OC estimation

According to the results of the linear mixed model analysis, the number of years of continued cultivation of croplands on former miombo woodlands does not have a significant effect on maize yield. The results of the ANOVA showed that the conversion of miombo woodlands to cropland, and subsequent continuous cropping, can have a temporary negative effect on SOC content in the first 2 - 7 years of cultivation. The major plant nutrients (N, P & K) on farmlands in both soil layers, however, did not show a significant change from the adjacent miombo woodland, and they did not decline over time. The results of both socioeconomic and soil analysis confirmed that the clearing of miombo woodland, and subsequent continuous cultivation by small-scale subsistence farmers, did not lead to a significant decline of the most important soil nutrients and maize yield, although the average yield was low (1.19 t ha^{-1}). This can be because the current farming system, which incorporates few trees in the croplands, fertilizing using manure, and leaving crop residues on the plot, is able to maintain some of the major plant nutrients. Besides, the woodlands are generally located on soils naturally poor nutrients, particularly N and extractable P (Frost 1996), and significant losses usually occur in soils with high concentrations of nutrients. The fact that the woodlands were degraded prior to conversion into crop land might also explain why there was no significant negative effect on the soil quality, and thus on crop yield. This implies that the OC of avoiding deforestation of the miombo woodlands does not decline over time due to a decline in land productivity. This further implies that it is reasonable to assume that present agricultural practices are sustainable in estimating OCs of not deforesting (clearing and cultivating), as in case of our study (Paper I).

5.3 Optimal wood harvest in miombo woodlands considering REDD+ payments

The optimal solutions in our model were different for the different scenarios. In the case of the first scenario, at any discount rate above 7.3 %, regardless of the price of charcoal, immediate harvest of all biomass is the optimal solution. This shows that if payment for carbon sequestration and storage is not taken into account, the interest rate is the important factor in determining optimal harvest levels. Regarding the second scenario, the price of CO_2 required to stop wood harvest ranged from 10 to 30 USD tCO_2e^{-1}, depending on the price of charcoal and discount rate. For the current price of charcoal (5 USD/bag), and interest rates between 5 and 10 %, 15 USD tCO_2e^{-1} is required to stop wood harvesting. In this case, given the price of charcoal, the price of CO_2 plays an important role in determining the optimal harvest level. For the lowest price of charcoal (2.3 USD/bag), 10 USD tCO_2e^{-1} would be sufficient to avoid wood harvesting completely for both high and low discount rates. For the highest price of charcoal (10 USD/bag) and the lowest interest rate, a CO_2 price of 30 USD tCO_2e^{-1} will be required to avoid wood harvesting. For a given price of CO_2 the role of interest rate in determining optimal harvest level becomes significant as the price of charcoal increases. The optimal solution for the third scenario, for the current price of charcoal (5 USD/bag) and discount rates 5.3 % and

10 %, the CO_2 price had to be 10 and 15 USD tCO_2e^{-1}, respectively. If emissions were not taxed, however, (fourth scenario), a CO_2 price of 10–40 USD tCO_2e^{-1}, depending on the interest rates, would prevent wood harvest until the biomass density becomes 60–100 t ha^{-1}. The CO_2 price required to stop wood harvesting was slightly lower than the price required if payments were not made for reduced degradation, regardless of the interest rate. However, this does not imply that it is cheap to stop wood harvesting if payment for biomass reduction below baseline degradation is considered. As in the case of stopping deforestation, stopping degradation of miombo woodlands through REDD+ would require a relatively high price of CO_2.

5.4 Past and future profitability of deforestation of miombo woodlands

Conversion of the miombo woodlands on public land into cropland has been profitable at a price of CO_2e lower than 9–13 USD CO_2e^{-1}. The lowest price corresponds to the global real prices of maize, while the highest corresponds to the local prices. The difference between local and global estimates is mainly explained by the fact that local prices of maize and the official exchange rate of Tanzanian shillings (TSH) were controlled by the Tanzanian state during the first half of the study period. Consequently, local price of maize officially seemed higher than the American price. Increasing the discount rate from 5.3 % to 10 % reduced the break-even price of a ton of CO_2e to 11 and 8 USD, respectively. Given the degraded state of woodlands in the common land in 1964, the shift from woodland to cropland could have been profitable even when we consider the social cost of CO_2 emissions. The conclusion depends on which price of CO_2 is considered realistic. The reduction of biodiversity and other important ecosystem services following deforestation was not included in our analysis. This negative externality could have reduced profitability of deforestation significantly. Maintaining the protected woodland, on the other hand, can be more profitable than the potential benefits of deforestation at a price of CO_2 higher than 6–9.5 USD CO_2e^{-1} for discount rates of 10 % and 5.3 %, respectively. The high discount rate used in this study is within the range of the discount rates (8–15 %) applied for agricultural projects in developing countries (Bond 2010). Besides, given the level of poverty persisting in the miombo areas, a discount rate of 10 % per annum may be a reasonable assumption. When wage rate was increased from zero to the minimum wage rate of 2,692 TSH man-day^{-1}, keeping the forest reserve for carbon sequestration became profitable at a price of CO_2 higher than 6 and 3.5 USD CO_2e^{-1} for interest rates of 5.3 % and

10 %, respectively. This implies that better employment opportunities in the area would make deforestation of the woodland in the reserve less profitable.

6 General discussion

6.1 Economic feasibility of avoiding deforestation and degradation through REDD+ in Tanzania

The overall financial feasibility of implementing a REDD+ policy at a specific site depends on the carbon (CO_2e) price required to cover mainly the OCs. The thesis is focused on OCs of deforestation and forest degradation in Tanzania. Those costs determine the compensation that must be paid to direct agents. Much of the interest in REDD+ is due to the perception that this compensation is low, since agricultural rent in most developing countries, including Tanzania, is low. In Papers I, III and IV we have reported farm-gate prices in USD tCO_2e^{-1} that may be required to stop deforestation or degradation, or make deforestation unprofitable. The price estimates varied significantly depending mainly on the biomass (carbon) density of the considered vegetation. The estimated prices were compared to the prices observed in international REDD+ agreements and on the European market for tradable quotas. Accordingly, the CO_2e prices required to stop deforestation of the montane forest were very low, regardless of the effects brought about by varying assumptions in factors like interest rate. The CO_2e prices required to stop deforestation and degradation of the miombo woodlands in general were, however, very high. It may be argued that the prices we used for comparison are low, and that significantly higher prices will be required in the future in order to limit global warming to 2 ^{o}C (Roberts 2014). The Norwegian government has applied taxes on CO_2 emissions for some time. At the moment they vary from 25 to 400 NOK tCO_2e^{-1}, i.e. 3.6–57.5 USD tCO_2e^{-1}. The lowest price applies to natural gas used by mainland industries, while the highest price applies to gas and oil used in oil exploration on the continental shelf (Ministry of Finance 2014). As of July 2014, carbon taxes existed in India, Japan, South Korea, Denmark, Finland, France, the Republic of Ireland, the Netherlands, Sweden, the United Kingdom, Norway, Switzerland, Costa Rica, parts of Canada, and parts of the United States. This implies that which price of CO_2 is considered high depends on how willing the affluent societies are to pay to reduce emissions through REDD+.

The level of carbon price required for REDD+ to be economically feasible also depends on the estimates of implementation and transaction costs. Adopting REDD+ involves costs of implementing the necessary policies to achieve reduced deforestation and forest degradation, or enhanced forest carbon stocks. These costs are as significant as OCs. Fisher et al. (2011) for example, reported that a carbon price required to cover implementation costs, the costs of meeting food and fuel demands sustainably, are higher (4.6–9.4 USD tCO_2e^{-1}) than those required to compensate OCs (3.2–5.5 USD tCO_2e^{-1}) in Tanzania. Moreover, compensating direct agents of deforestation and forest degradation (e.g. farmers and charcoal producers) requires setting up a REDD+ system, and this involves substantial transaction costs. In a situation with pronounced discrepancies between *de jure* and *de facto* land tenure, as well as recognized corruption and illegal timber trade (Brockington 2008, Smith 2015), those costs may be considerable. Pearson et al. (2014) showed that including transaction costs could increase the carbon price necessary to cover REDD+ costs by up to 30 %. Such costs are however, not included in this study. This implies that the carbon price required to cover all REDD+ costs is much higher than those reported in this study. Nevertheless, along with REDD+, introducing payments for other important ecosystem services provided by forests and woodlands could potentially reduce the overall cost of avoiding or reducing deforestation and forest degradation. Moreover, investing in existing forest or nature reserves could minimize the cost of implementing the policy (Papers I and IV). Creating a system by which the local community could continue harvesting mainly wood and other products from the surrounding forests and woodlands without degrading it could also potentially reduce REDD+ payments required to offset OCs (Paper I).

6.2 Factors that contribute to variations in carbon (CO_2e) price estimates

There are several factors which could potentially affect estimates of carbon (CO_2e) prices. Our price estimates were significantly affected by variations in assumptions in discount rate, valuing farmers' own labor, and potential forest use rules following the implementation of REDD+.

In order to compare revenues and expenditures at different points of time, a constant discount rate is commonly used, although more sophisticated methods have been suggested and sometimes applied (Goulder and Williams III 2012). The choice of discount rate is not simple (Baumol 1968). It is obviously such that the appropriate rate is different for a farming household on the one hand and for the society as a whole on the other. For an individual investor, it would be reasonable to apply a rate reflecting the opportunity cost of capital. This may vary according to investment opportunities, which depends both on the investor (e.g., risk aversion) and the business climate at the time. However, Tanzanian smallholder households should be considered both investors and consumers. Probably they have limited investment opportunities and limited capital endowments (Holden and Shiferaw 2002), and their propensity to save is likely to be low. As consumers, they might have time preferences in the range of 6–7 % (Robberstad 2005). For the Tanzanian society the appropriate discount rate to be applied in management of natural resources such as forests and woodlands depends on larger issues like population growth and expected growth in welfare among the population (Markandya and Pearce 1991). In a CBA based on data from 2003 to 2007, Wiskerke et al. (2010) used real discount rates of 7 to 18 %. Ngowi et al. (2007) used a real interest rate of 3 % charged by Tanzania National Microfinance Bank in 2004. We used real discount rates of 5.3 % and 10 % in papers I, III, and IV. This seems as a reasonable span of discount rates for smallholder households in Tanzania during the last decade. In paper IV we undertook a CBA of deforestation, using Maseyu village as a case. In this case deforestation was assessed more from a social point of view than from the point of view of individual farmers, although the decision to clear the woodland was made by smallholders with no knowledge of GHG emissions. Consequently, a social discount rate (2–5 %) was more appropriate than a private one in the CBA. Our higher discount rate of 10 % is in line with Sathaye et al. (2001) who used a real discount rate of 10 % for Tanzania and some other countries in their evaluation of carbon sequestration potentials in forestry. It is also in line with Fisher et al. (2011), who used the same discount rate for Tanzania in their estimation of opportunity and implementation costs of REDD+.

Cost of labor is an important component of agriculture and forest production which should be accounted for when estimating costs of production. Labor can generally be categorized into family labor and hired labor. Since labor is abundant in the study areas in particular and in Tanzania in general, most farmers depend on family members for labor. Valuing a farmer's own labor is difficult (Fisher et al. 2005, Le 2009), and assumptions has to be made on the wage rates when estimating costs of labor. The country's minimum wage rate for agricultural services, or the wage rates applied for other activities in the particular areas, can be used as bases for estimating farmer's own labor. However, considering positive opportunity cost of labor while the actual opportunity cost of labor is nearly zero can underestimate the level of payment required to compensate land owners/users for their forgone benefits (Paper I). Moreover, crop production is significant in terms of providing employment opportunities for the local people as shown in Paper I. This implies that in addition to economic benefits, the local communities will forgo benefits in terms of lost employment opportunities by not continuing the business as usual activities. This further indicates that in places where there are no readily available alternative livelihoods, forgone employment opportunities need to be considered when a REDD+ policy is designed.

In the calculation of OCs of stopping deforestation, we assumed that villagers could continue harvesting wood at a sustainable level after signing the REDD+ contract. This would secure carbon stocks at the present level in the forest while the harvest would offset about half of the agricultural rent lost due to prohibition of further deforestation. However, if wood harvest is also ceased, biomass and carbon would be accumulated in the forest for some time since the forest, particularly the miombo woodlands, are hardly at their maximum density at present. Some buyers of REDD+ credits might insist that such accumulation should be part of the environmental service paid for. They may also not trust that wood harvest would be limited to sustainable levels, and therefore insist that all wood harvest should cease. In such cases, our results indicated that the REDD+ payments required to offset OCs would be about 50 % higher than those reported in Paper I.

Our analysis of agricultural rent showed a high variation of NPV estimates among farming households (Paper I). The majority of farmers earned little income from the cultivation of crops, and only a few were able to make high profits. This has an implication on the REDD+ payment design. It shows that a separated payment system, where each landowner/user receives just his/her OC, might be required. Different payment systems have different cost implications. Wertz-Kanounnikoff (2008) indicated that separated payment system are considered to be cost effective compared to uniform payment system, where every landowner/user receives the same amount of compensation.

In Paper I a detailed calculation of revenues from wood harvested during land clearing (deforestation) was made. This included an estimation of how much of the standing volume would be used for different wood products. In the montane forest, we assumed that 25 % of the timber volume would be used for sawn wood, 11 % for poles, and 16 % for tool handles. Only

48 % of the standing biomass was assumed to be burned following deforestation. This assumption could have led to an overestimation of the amount of CO_2 released to the atmosphere or the amount of carbon that could be saved by REDD+. This further implies that the estimates of CO_2e prices to cover OCs of not deforesting the montane forest are underestimated by nearly 50 %. Similarly, for the miombo woodland, we assumed that 40 % would be used for charcoal production. The same assumption about deforestation of miombo was adopted in Paper IV. In Paper III, however, we made the simplified assumption that all aboveground woody biomass would be used in charcoal production. Since some tree species are not considered suitable for charcoal making, this overestimated the potential revenue of charcoal making. Consequently, the price of CO_2e required to stop degradation was also overestimated. If only 40 % of the wood in miombo is used for charcoal, estimated REDD+ payments for our lowest charcoal price (2.3 USD/bag) may be more realistic than the other alternatives.

In Paper I the agricultural rent after deforestation was estimated based on a thorough household survey. One of the important factors affecting the value of rent was crop type. In the surveyed villages, farmers cultivated cash crops like sugar cane and rice as well as a number of crops both for subsistence and the market. In many cases, farmers practiced intercropping of maize, pulses and a variety of vegetables. When the profitability of deforestation was studied in Paper IV, we made the simplified assumption that maize was the only crop grown. Maize is the main crop in the drier lowland areas of Morogoro region, so we considered this simplification justified. Moreover, in the *Ex post* analysis, historical prices were needed. We encountered serious difficulties finding historical time series of prices for crops other than maize. Prices of maize are relatively low compared to prices of many other crops. Therefore, the agricultural rent, and thus the break-even price of CO_2e estimated in Paper IV, is slightly lower than those reported in Paper I. This contributes to a slight underestimation of the profitability of deforestation.

Estimates of social costs of carbon (SCC) are highly uncertain (Klein et al. 2007). Tol (2008) reported that the SCC for 2005 had an average value of 43 USD tC^{-1} (158 USD tCO_2e^{-1}) with a standard deviation of 83 USD tC^{-1}. The wide range of estimates is explained mostly by underlying uncertainties in the science of climate change (e.g., the climate sensitivity, which is a measure of the amount of global warming expected for a doubling in the atmospheric concentration of CO_2), different choices of discount rate, different valuations of economic and non-economic impacts, treatment of equity, and how potential catastrophic impacts are estimated. Other estimates of the SCC spanned at least three orders of magnitude, from less than 1 USD tC^{-1} to over 1,500 USD tC^{-1}. The true SCC is expected to increase over time. The rate of increase will very likely be 2–4 % per year. When we discussed the price of CO_2 in relation to REDD+, we did this mainly in relation to what emitting industries and governments have been willing to pay for carbon sequestration in forests, and not in relation to the social cost of CO_2 emissions.

6.3 Uncertainties in OC estimation

Uncertainties associated with estimating the present value of net returns from agriculture and thus OCs, include expected rates of change in agricultural productivity (Paper II), as well as fluctuations in market prices for agricultural products (Paper IV).

Using current levels of agricultural productivity for NPV estimation can under- or overestimate the agricultural rent. There is a potential for increasing yields on existing cropland in response to crop prices, and improved technology and management. There is also a potential for decreasing yields after continuous cultivation. The latter case was addressed in Paper II, where it was shown that the farmers have managed to maintain the productivity of the land. The average yield was, however, very low (1.19 t ha^{-1}) and in line with the average maize yield in Tanzania (0.7 - 1 t ha^{-1}) (Fisher et al. 2011). Agricultural productivity in Tanzania and other sub-Saharan countries is generally below its potential, 5 t ha^{-1} yr^{-1} (Sanchez et al. 2007, Rockström et al. 2009, Sánchez 2010). This indicates the possibility for boosting crop yields on existing farmlands.

Fluctuation in market prices for agricultural products could significantly affect the estimates of agricultural rent. Prices for crop outputs, like any other commodities, are expected to fluctuate. The fluctuations are partly caused by local circumstances and government policies (as shown in Paper IV), and partly due to local demand and supply.

7 Conclusions and future research

The overall objective of the study was to assess the economic feasibility of the monetary-incentives-based climate change mitigation measure, REDD+ in Tanzania. From our four independent, but interrelated, studies, it can be concluded that implementing the policy in an efficient way should start with better protection of already existing forest or nature reserves in areas with high biomass density (> 100 t ha^{-1}), mainly the EAM and other highland areas. Farmers living next to similar forests which are not included in nature reserves can be offered a reasonable compensation for not deforesting. Several factors which can potentially affect the feasibility of the implementation of the policy measure have been identified. However, the significance of these factors is revealed when the biomass (carbon) density of the vegetation is as low, as in the miombo woodlands. Less efficient farmers would probably accept very low compensations, but such payments might require additional initiatives to generate employment opportunities for rural people. REDD+ is probably not sufficient to significantly affect the deforestation and degradation of miombo woodland that has already been subject to exploitation. Broader policies of land tenure reform, agricultural development and urban energy supply might be required in order to slow the destruction of such low-density vegetation.

Our models used for economic analyses of REDD+ are based on fixed market model which is space limited (site specific). This kind of models are not suited for estimating potential large-scale effects of changes in land use incentives across regions, which are likely to occur with regional or global implementation of REDD+. For example, reductions in deforestation could lower the supply of crop outputs and/or forest products, raising their prices and thus both the costs of REDD+ and the risks of displacement of deforestation elsewhere (leakage) (Lubowski and Rose 2013). For the estimation of economy-wide effects of reduced deforestation and forest degradation, partial equilibrium models may be more appropriate (Angelsen et al. 1999, Sathaye et al. 2005, Aaheim et al. 2011).

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PAPER I

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ORIGINAL ARTICLE

Monetary incentives to avoid deforestation under the Reducing emissions from deforestation and degradation (REDD)+ climate change mitigation scheme in Tanzania

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Abstract The paper estimates and compares the level of Reducing Emissions from Deforestation and Degradation (REDD+) payments required to compensate for the opportunity costs (OCs) of stopping the conversion of montane forest and miombo woodlands into cropland in two agro-ecological zones in Morogoro Region in Tanzania. Data collected from 250 households were used for OC estimation. REDD+ payment was estimated as the net present value (NPV) of agricultural rent and forest rent during land clearing, minus net returns from sustainable wood harvest, divided by the corresponding reduction in carbon stock. The median compensation required to protect the current carbon stock in the two vegetation types ranged from USD 1 tCO_2e^{-1} for the montane forest to USD 39 tCO_2e^{-1} for the degraded miombo woodlands, of which up to 70 % and 16 %, respectively, were for compensating OCs from forest rent during land clearing. The figures were significantly higher when the cost of farmers' own labor was not taken into account in NPV calculations. The results also highlighted that incentives in the form of sustainable harvests could offset up to 55 % of the total median OC to protect the montane forest and up to 45 % to protect the miombo woodlands, depending on the wage rates. The findings suggest that given the possible factors that can potentially affect estimates of REDD+ payments, avoiding deforestation of the montane forest would be feasible under the REDD+ scheme. However, implementation of the policy in villages around the miombo area would require very high compensation levels.

Keywords Agricultural rent · Forest rent · Miombo woodland · Montane forest · Opportunity cost · REDD+ · Sustainable harvest

1 Introduction

Conversion of forestland to agricultural land has been one of the main proximate causes of tropical deforestation (Barbier and Burgess 1997; Kaimowitz and Angelsen 1998; FAO 2010;

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Kissinger et al. 2012), and subsequent emissions of greenhouse gases and loss of other important ecosystem services (FAO 2010). This activity has been estimated to account for about 80 % of deforestation globally (Kissinger et al. 2012) and up to 12 % of total human-induced CO_2 emissions (van der Werf et al. 2009). Moreover, deforestation due to agricultural expansion is expected to increase in the near future (Kissinger et al. 2012) despite the fact that, for example, tropical forests play an important role in regulating global climate by serving as sinks for carbon, storing about 50 % of the terrestrial organic carbon (FAO 2005). In the global climate change mitigation agenda, this led, in 2008, to the development of the United Nations' policy measure Reducing Emissions from Deforestation and Forest Degradation (REDD), which in 2010 became REDD+ (Reducing Emissions from Deforestation and Degradation, and enhancing forest carbon stocks).

REDD was originally a financial-incentives-based policy measure developed as a means to protect forest carbon stocks from being released into the atmosphere as a result of deforestation and forest degradation (Wertz-Kanounnikoff and Kongphan-apirak 2009; Dudley 2010). REDD+ includes the possibility of offsetting carbon emissions through forest conservation, sustainable management of forests, and enhancement of forest carbon stocks (Bosetti and Rose 2011; Angelsen et al. 2012). Moreover, the policy measure provides a recognized system of payment for ecosystem services related to carbon sequestration and storage, whereby payments are made on the basis of performance (Wunder and Wertz-Kanounnikoff 2009).

REDD+ involves restrictions on local use of forestland and resources. However, about 1.6 billion people depend on tropical forests for their daily needs (World Bank 2004), and about 13 million ha of forest are cleared annually to provide livelihoods, incomes, and employment for millions of people in the tropics (FAO 2010; Kissinger et al. 2012). REDD+ will therefore impose considerable opportunity costs (OCs) on local communities (Wollenberg and Springate-Baginski 2009; Springate-Baginski and Wollenberg 2010). The OCs refer to the net benefits forgone by landowners/users as a result of not deforesting or degrading forests. The idea behind the REDD+ scheme is that such costs should be compensated in order to eliminate or reduce deforestation and forest degradation without affecting the livelihoods of local communities.

Several studies have shown that avoiding deforestation would cost less than USD 5 tCO_2^{-1} (Osborne and Kiker 2005; Grieg-Gran et al. 2006; Stern 2007; Bellassen and Gitz 2008; Potvin et al. 2008; Yamamoto and Takeuchi 2012). Even though higher costs have been estimated (e.g., Kindermann et al. 2008; Butler et al. 2009), REDD+ is generally assumed to be a relatively cheap mechanism seen as a cost-effective climate change mitigation mechanism compared to industrial mitigation measures.

Most REDD+ cost estimates are based on payments required to offset OCs as the main cost component. The payments vary considerably among and within regions, depending on a number of ecological and economic factors (Angelsen 2008; Grieg-Gran 2008; Olsen and Bishop 2009). OCs of not converting forests to cropland vary greatly, depending on the types of farming systems and crops. For example, small-scale subsistence farming does not generally generate produce with quantifiable economic value and therefore the estimated OC of stopping such a farming system is usually very low, as shown by several studies (e.g., Bellassen and Gitz 2008; Olsen and Bishop 2009), compared to the cost of paying a landowner/user to not convert forests to large-scale commercial agriculture such as palm oil production (Butler et al. 2009) or soybean cultivation (Kindermann et al. 2008). Most OC calculations overlook the non-monetary benefits derived from agricultural and forestry activity that a landowner/user would forego by not clearing or degrading forests due to the difficulty in calculating them. However, some studies show that incorporating such costs into REDD+ projects increases the level of compensation (Karky and Skutsch 2010), implying that REDD+ compensation schemes may not be as cheap as many estimates suggest. Moreover, compensation values estimated for moist tropical forests with carbon densities of greater than 200 tC ha^{-1} in, for example, Brazil (Olsen and Bishop 2009), Cameroon (Bellassen and Gitz 2008), Guyana (Osborne and Kiker 2005), and Indonesia (Yamamoto and Takeuchi 2012) are very small, below USD 5 tCO_2^{-1}. However, such estimates cannot be treated as representative of dry tropical forests, such as those Tanzania in which carbon densities are less than 100 tC ha^{-1} (Munishi et al. 2010). Further, significant variations have been reported in the amount of compensation required to protect relatively intact forests, compared to degraded forests of the same type (Olsen and Bishop 2009). Other factors that affect the compensation estimates include variations in assumptions regarding the cost of labor (mainly family labor), the discount rate, time horizon, the degree of access to forests permitted after the implementation of the policy, and how net costs of conversion are treated (Grieg-Gran 2008; Karky and Skutsch 2010).

The aforementioned issues suggest the need for localized estimates of REDD+ payments and for identifying conditions and factors that will affect the feasibility of the policy measure and thereby inform decisions as to where to establish projects. To address these issues, we therefore conducted a study in Morogoro Region, Tanzania. Two vegetation types representing a humid forest and a dry tropical forest were considered. The main objective of this paper is to estimate and compare monetary incentives required to stop the conversion of montane forest and miombo woodlands into cropland under different cropping systems, and thus evaluate the feasibility of REDD+ policy in two agro-ecological zones in Tanzania. In addition, the effects of different assumptions regarding valuing farmers' own labor in crop production as well as possible forest management rules that apply to forest use following the implementation of the scheme on the level of REDD+ payments required are examined to determine their implications for the policy design.

2 Forest status in Tanzania

Tanzania possesses about 35 million ha of forests and woodlands, covering 40 % of the country's total land area (FAO 2010). About 90 % of the forested and wooded area is made up of miombo woodlands (Malimbwi et al. 2005). Miombo, a collective name for species of the genera *Brachystegia*, *Julbernardia*, and *Isoberlinia*, is a common vegetation type in large parts of central, south, and eastern Africa (Campbell 1996). Other vegetation types include montane forests, mangrove forests, acacia savannah, and coastal forests (Burgess et al. 2010). About 52 % of the forests and woodlands in the country are within protected areas, and the remaining percentage is on village or general (*de facto* open access) lands (Zahabu et al. 2007; Mbwambo et al. 2012). Tanzania is one of a number of countries currently experiencing a high rate of deforestation and is planning to implement a REDD+ policy. It has been estimated that the country lost an average of 403,000 ha (about 1.02 %) of its forests and woodlands per year during the period 1990–2000 (FAO 2010). During the same period, the percentage loss was higher for miombo woodlands (13 %) compared to the Eastern African coastal forest mosaic (7 %), mangrove forest (2 %), and forests of the Eastern Arc Mountains (EAM) (1 %) (Burgess et al. 2010). Between 2000 and 2010, the annual forest loss increased to 1.1 % (FAO 2010). Agricultural expansion has been identified as one of the main drivers of deforestation in Tanzania (Makundi and Okiting'ati 1995; Angelsen et al. 1999; Burgess et al. 2002; Luoga et al. 2005; Kissinger et al. 2012). In addition, particularly the miombo woodlands have been subject to extensive extraction of wood for charcoal making (Monela et al. 1993; Luoga et al. 2005; Nduwamungu et al. 2008). It has been suggested that REDD+ monetary incentives may help to reduce the problem of deforestation and degradation in the Tanzania (Zahabu et al. 2007).

3 Materials and methods

3.1 Study sites

Our socioeconomic survey was conducted in seven villages within Morogoro Region: Kunke, Maseyu, Mlimbilo, Ng'ungulu, Nyandira, Tchenzema, and Vinile (Fig. 1). The first three aforementioned villages are located at an average altitude of 400 m a.s.l., hereafter referred to as the lowland zone. The remaining four villages are located between 1,000 m a.s.l. and 2,668 m a.s.l., hereafter referred to as the highland zone. The two agro-ecological zones comprise two distinct vegetation types: miombo woodlands in the lowland zone and montane forest in the highland zone.

Kunke and Mlimbilo are located in Mtibwa Ward, 120 km north of Morogoro town. The villages cover an area of about 24,000 and 13,600 ha and have about 3,500 and 2,000 inhabitants, respectively. The climate of the area is sub-humid tropical, with a mean annual rainfall in the range of 800–1,200 mm. There are two rainy seasons, the short rains from October to December and the long rains from March to June. Mean annual temperature varies between 28 °C and 31 °C. The area includes settlements, a sugar factory, croplands, sugarcane (*Saccharum officinarum* L.) and teak (*Tectona grandis* L. leaf) plantations, grazing land, open scattered miombo woodlands, and part of a protected miombo woodland known as the Wami-Mbiki wild animals management area (WMA). The inhabitants depend mainly on agriculture for their livelihoods. They practice small-scale and medium-scale farming and cultivate crops for subsistence [maize (*Zea mays* L.)] and for marketing [rice (*Oryza glaberrima* S.), sesame (*Sesamum indicum* L.), and sugarcane]. WMA is a community-based conservation area that was established in 1999. The area is located in two regions, Morogoro Region and Tanga Region. It covers a core area of about 3,000 km^2 and a buffer area of about 1,200 km^2 (Madulu 2005). The WMA is surrounded by 24 villages including Kunke and Mlimbilo, and houses about 65,000 people in total; it covers 65 % of Kunke and 47 % of Mlimbilo. The woodlands inside the WMA have suffered from extensive tree cutting for charcoal production, and agricultural expansion and encroachment.

Maseyu is located in Gwata Ward, about 50 km northeast of Morogoro town and 150 km west of Dar es Salaam (Fig. 1). The climatic conditions and rainfall pattern in Gwata Ward are similar to those in Mtibwa Ward. The village of Maseyu covers approximately 36,000 ha and has about 2,000 inhabitants. It comprises settlements, croplands, open miombo woodlands, village reserves, part of Kitulangalo Forest Reserve (KFR), and a part of the WMA. About 80 % of the households depend on crop production (Nduwamungu et al. 2008). The local farming system is characterized by small-scale rain-fed crop cultivation for both subsistence consumption [maize, millet (*Eleusine coracana* L.), and sorghum (*Sorghum bicolor* L.)] and for marketing (sesame). The inhabitants are highly dependent on forest resources in protected and unprotected woodlands, both for their own consumption (firewood, fruit and vegetables, and wood for poles) and for commercial purposes (charcoal). The KFR spans two villages: Gwata and Maseyu. The reserve covers an area of about 435 ha in Gwata and 1,705 ha in Maseyu. The vegetation type is generally characterized as open, dry miombo that is dominated by the tree species *Julbernadia globiflora*, *Brachystegia boehmii*, and *Pterocarpus rotundifolius* (Luoga et al. 2000). The part of the forest reserve located in Maseyu is managed jointly by the central government and the village, while the part in Gwata is managed by the

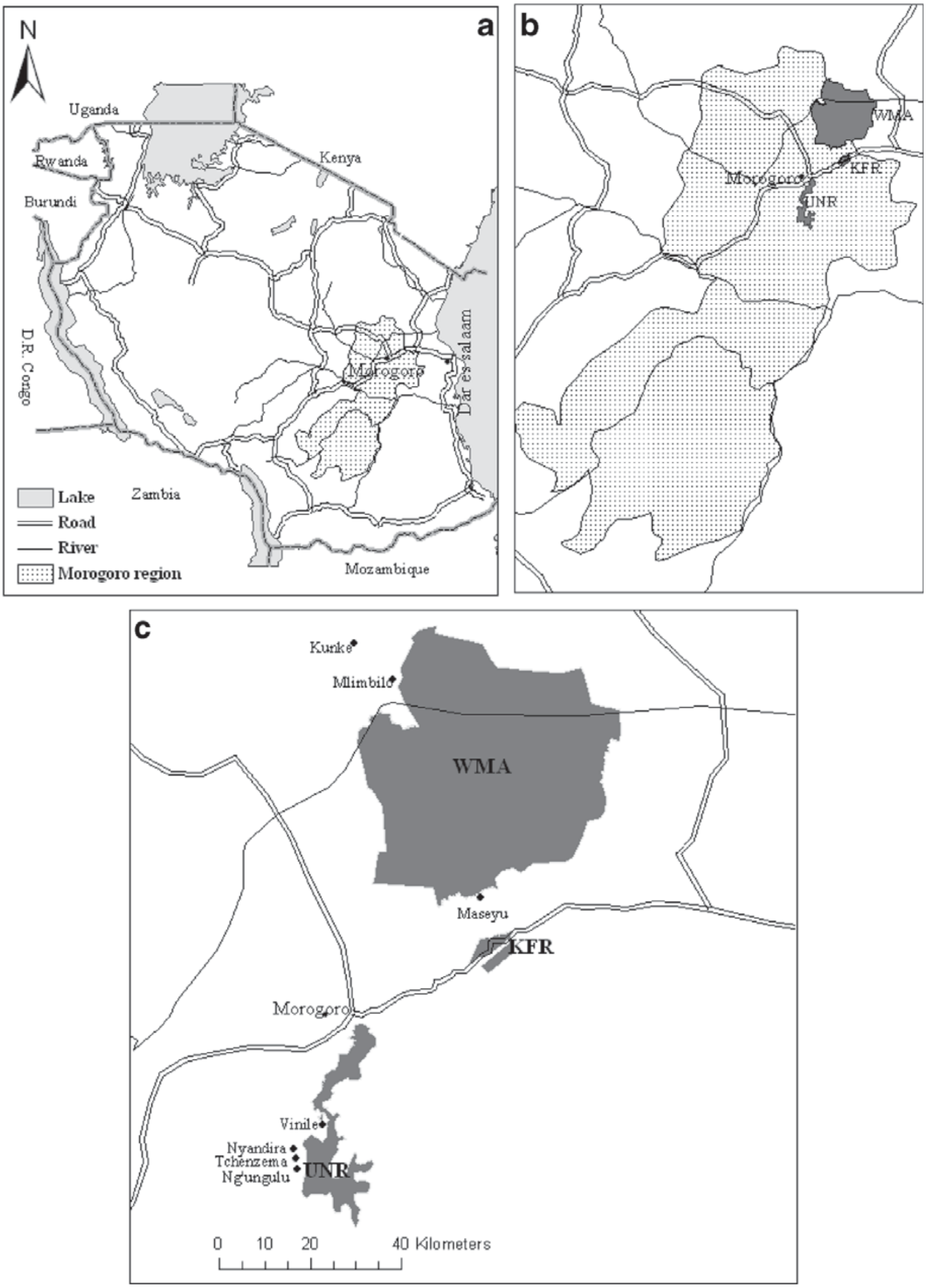

Fig. 1 Tanzania (**a**), the location of Morogoro region (**b**), and the study villages and protected forests within the region (**c**)

central government through Sokoine University of Agriculture in Morogoro town. The KFR was established in 1985 (Luoga et al. 2002). However, the current management systems have been practiced since 1995 in Gwata and since 2000 in Maseyu. The reserve is formally protected, but in practice, tree cutting is common practice and there have been some cases of conversion into agricultural land. An estimated 1.2 m^3 ha^{-1} of wood is illegally harvested from the reserve annually (Luoga et al. 2002). Moreover, in the period 1975–2000, closed woodland in the reserve and the surrounding area declined by 45 %, while open woodland in the surrounding area increased by 42 % (Nduwamungu et al. 2008).

Ng'ungulu, Nyandira, Tchenzema, and Vinile are located in Mgeta Division, about 200 km west of Dar es Salaam (Fig. 1). Mgeta Division covers an area of 1,800 km^2 and includes four wards and 28 villages with a total population of about 46,000. The climate in the area is tropical, with an average annual rainfall in the range of 1,000–2,000 mm. The rainy season lasts from November to May. The mean annual temperature varies from 15 °C to 21 °C (Kapilima 1994). The surrounding farmlands extend up to the border of Uluguru Nature Reserve (UNR), at about 2,000 m a.s.l., but rarely extend into the reserve (Frontier-Tanzania 2005). The inhabitants in areas to the UNR practice intensive small-scale farming of both subsistence crops [maize and pulses such as beans (*Phaseolus vulgaris* L.), chickpeas (*Cicer arietinum* L.), and peas (*Pisum sativum* L.)] and cash crops [vegetables such as cabbage (*Brassica oleracea* L.), potato (*Solanum tuberosum* L.), and tomato (*Solanum lycopersicum* L.)], and rely mainly on family members for labor. The UNR is part of the EAM, a chain of mountains stretching from the Taita Hills in southern Kenya through eastern Tanzania to the Udzungwa Mountains of south-central Tanzania. The nature reserve covers an area of approximately 24 km^2 and is surrounded by 57 densely populated villages (FBD 2009). It consists of sub-montane forests (below 1,500 m a.s.l.), montane forests (1,600–2,400 m a.s.l), and upper montane forests (above 2,400 m a.s.l), and receives the highest rainfall (up to 4,000 mm $year^{-1}$) in Tanzania (Lovett and Pócs 1993). Rivers originating in the reserve are the main supply of water to the local communities, as well as to Morogoro town and Dar es Salaam (Lundgren 1978). The UNR is one of the world's biodiversity hotspots (Poynton et al. 2007). It also plays an important role as a carbon reservoir, currently storing about 10.3 million tons of carbon (FBD 2010). The reserve, which is managed by the central government, has been protected since the 1910s; in 1950, it was gazetted, and since then the cutting of trees has been officially prohibited. However, illegal harvesting of wood from the UNR has continued. Moreover, between 1955 and 2000, 25 % of the forest was lost, mainly due to agricultural expansion (Burgess et al. 2002). To mitigate the impact, the government allowed households in the surrounding villages to collect firewood, fruits, herbs, and other non-wood forest products for their own consumption, two times per week (FBD 2009). Uluguru Nature Reserve comprises four separate forest reserves, Uluguru North FR, Uluguru South FR, Bunduki FR, and Bunduki Gap FR. Our study was conducted in Mgeta Division, which covers the southwestern side of the Uluguru Mountains, within Uluguru South FR.

3.2 Data

The data were collected over the course of 5 months, between September 2011 and January 2012, from communities located in the seven study villages. A total of 112 households were randomly selected from the four villages in Mgeta Division (Ng'ungulu, Nyandira, Tchenzema, and Vinile), 65 from the two villages in Mtibwa Ward (Kunke and Mlimbilo), and 54 from the village of Maseyu in Gwata Ward. Basic demographic information, as well as information relating to costs and revenues associated with crop production and forestry, local prices of all inputs and outputs, as well as labor costs, was obtained using structured questionnaires. Further information was collected through focus group discussions to triangulate and verify the information obtained from households as well as to obtain qualitative information. In addition, we visited local market places to gather information on prices of inputs and outputs. Moreover, secondary sources were used to obtain data on the carbon storage potential of different types of vegetation and land uses.

3.2.1 Estimating REDD+ payments to offset OCs

The OC of forest protection can be defined as the forgone net benefits from the best alternative land uses (Bond et al. 2009; Olsen and Bishop 2009; Angelsen et al. 2012) and are payments required to compensate forest owners or users for their forgone benefits (Angelsen 2008). REDD+ payments to offset OCs can be estimated as the net present value (NPV) of the next best use of forestland divided by the associated reduction in carbon stock (Wertz-Kanounnikoff 2008). OC estimates will depend on the rules that apply to forest use after the REDD+ contract has been signed. For simplicity, we assumed that deforestation should stop immediately, while wood harvesting could continue in a sustainable way. Here we defined sustainable harvest as the mean annual increment (MAI) of the forest or woodland under consideration. We therefore estimated the REDD+ payments to offset the OCs of stopping conversion of the two vegetation types considered in our study as the NPV of agricultural rent and forest rent during land clearing, minus the net returns from sustainable wood harvest, divided by the corresponding possible reduction in carbon stock.

3.2.2 Estimating agricultural rent

Data on crop production were collected from 606 sample plots. The size of the sample plots ranged from 0.1 to 2.0 ha in Mgeta Division, 0.4 to 5.0 ha in Mtibwa Ward, and 0.4 to 6.0 ha in Gwata Ward. The percentage share of each crop type cultivated in each village is presented in Table 1. We estimated the financial returns from the major crops grown at each village. The costs of crop production included the cost of land clearing, seeds, fertilizers, pesticides and fungicides, labor required for different activities, and transportation to the local market, and we obtained from local markets the prices of each input and each type of crop produce. The median yield and average price of the major crops cultivated in each village are summarized in Tables 2 and 3, respectively. Due to the difficulty of valuing a farmer’s own labor (Fisher et al. 2005; Le 2009), we applied and compared three different wage rates: (1) the reported wage rate in the study villages (hereafter referred to as the “village wage rate”), (2) the minimum wage rate for agricultural labor in Tanzania (“minimum wage rate”), and (3) a wage rate equal to zero (“zero wage rate”) which assumed an opportunity cost of labor as zero. The net benefit (NB) of each crop type was calculated

Table 1 Percentage share of crops cultivated in each study village

Village	Crop type (% share)									
	Maize	Sugarcane	Rice	Maize and sesame	Maize and millet	Millet and sesame	Vegetables	Pulses	Maize and pulses	Maize and vegetables
Kunke	50	13	16	21						
Maseyu	49			18	18	15				
Mlimbilo	76	6	14	4						
Ng’ungulu	19						1.5	4	74	1.5
Nyandira	8.5						13	6	50	22.5
Tchenzema	11						4	10	47	28
Vinile	13								74	13

Table 2 Median harvest (ton ha^{-1}) of the major crops cultivated in each study village

Crop type	Village						
	Kunke	Maseyu	Mlimbilo	Ng'ungulu	Nyandira	Tchenzema	Vinile
Maize	1.24	0.62	0.99	0.49	1.78	0.67	0.20
Sugarcane	19.77		49.00				
Sesame	0.50	0.30	0.86				
Rice	0.88		0.53				
Vegetables				0.49	1.73	3.08	
Pulses				0.49	0.37	0.30	0.43

as the difference between the total value of the crop harvest and the value of all production factors except land. Assuming that present agricultural practices are sustainable and that the relative prices of products and factors are constant, the NPV of land can be calculated as annual NBs divided by a constant discount rate. However, the assumption that the current yield estimates can reflect past and future yield values might lead to underestimates or overestimates of past and future estimates, respectively, as the croplands considered in our study were not representative of recently deforested lands. Further, the choice of the appropriate discount rate is far from an obvious and straightforward decision (Howarth and Norgaard. 1992). We chose a nominal discount rate based on the rate of lending by the Bank of Tanzania as of January 2011 (12 %) (BOT 2011). The real interest rate (*r*) was estimated by adjusting the nominal discount rate for inflation using the Fisher equation

$$r = \frac{1+i}{1+\pi} - 1$$

Where *i* is the nominal interest rate and π is the inflation rate. The inflation rate of all items for the period January 2010 to January 2011 was 6.4 % (BOT 2011). Accordingly, we used a discount rate of 5.3 %. The median agricultural NPV per hectare in each village was obtained using the formula

$$\mathrm{NPV} = \mathrm{FR} + \alpha_\mathrm{i}(\mathrm{NB_i}/r) + \ldots\alpha_\mathrm{n}(\mathrm{NBn}/r)$$

Table 3 Average price (USD kg^{-1}) of the major crops cultivated in each study village

Village	Price (USD kg^{-1})					
	Maize	Sugarcane	Sesame	Rice	Vegetables	Pulses
Kunke	0.22	0.17	0.82	0.91		
Maseyu	0.25		0.64			
Mlimbilo	0.22	0.02	0.48	0.93		
Ng'ungulu	0.34				0.29	0.27
Nyandira	0.26				0.16	0.47
Tchenzema	0.29				0.14	0.39
Vinile	0.27					0.38

Table 4 Economic parameters used to estimate rents to firewood, poles, timber, and tool handles

Product type	Quantity per hectare	Unit	Labor cost per unit (USD)	Price per unit (USD)
Firewood	0.90	Ton	0	106.00
Poles	170	Each	1.62	12.72
Timber	15.32	m^3	39.60	56.71
Tool handles	513	Each	0.32	0.64

where FR is the net revenue obtained per hectare from forest clearing, NB_i represents the median NBs per hectare from the ith most cultivated crop in each village, $\alpha \in [0, 1]$ is the ratio of cultivation of ith crop per hectare, and r is the real discount rate.

3.2.3 Estimating forest rent

Montane forest The montane forests are extensively used for harvesting wood for tool handles, poles, and timber. The tree species used for these products were identified and their net profits were estimated. Timber-producing species account for approximately 25 % of the total average standing volume (319 m^3 ha^{-1}). Tree species important for making poles and tool handles accounted for respectively 11 % and 16 % of the total average tree density (539 stems ha^{-1}). Timber volume was estimated using 63 % log recovery and 30 % timber recovery (Muthike et al. 2013). In contrast to the production of agricultural produce in the studied villages, the production of logs and timber requires labor that is more skilled. Hence, it is assumed that labor is hired for these activities. Wood extracted for making the different products is considered to be a free good and thus is available free of cost to the producer.

The collection of firewood from the reserve is assumed to be less or equal to the MAI of the forest, and therefore sustainable harvesting means only the collection of firewood. A household collects two head loads of firewood per week, and an average weight of a head load is about 13 kg (Mitinje et al. 2007). About 16,000 households depend on the nature reserve for firewood. The total biomass of firewood collected per hectare was therefore estimated as the number of households multiplied by the average annual consumption of a household divided by the total area of the forestland. The NPV was then calculated by dividing the value by the real interest rate, which was 5.3 %. The economic parameters that we used to estimate rents to firewood, poles, timber, and tool handles are presented in Table 4.

Miombo woodlands Most of the information on the miombo woodlands was derived from the data we collected from the village of Maseyu (Gwata Ward), and we assumed that the collected data were also representative of similar miombo woodlands in Mtibwa Ward. The average standing volume on public land (degraded miombo) is 14 m^3 ha^{-1} (Zahabu 2008). We estimated that the average standing volume in the forest reserve (dense miombo) in 2011 was 65 m^3 ha^{-1}, on the basis of inventory data that was collected in the same year. The MAI of the woodlands around the study villages is estimated to be 2.9 Mg ha^{-1} for regrowth miombo and 3.7 Mg ha^{-1} for old-growth miombo (Ek 1994), equivalent to a volume of 3.41 m^3 ha^{-1} and 4.35 m^3 ha^{-1}, respectively, using a 0.85 conversion factor from biomass (ton) to volume (m^3) (Malimbiwi et al. 1994). Tree species used for charcoal making represent 40 % of the standing volume. One cubic meter of wood yields 4.3 bags of charcoal (56 kg/bag), and the labor required to produce one bag of charcoal is 2.3 person-days (Hofstad 1997; Luoga et al. 2002). The cost of physical inputs, such as axes, machetes, and rope, is approximately USD 6.4. Such inputs are assumed to last for 5 years. We found that the average price of one bag of charcoal ranged from USD 5 at the kiln site to USD 6.3 at the road side. The same assumption as for the agricultural rent was made for estimating cost of labor required for different activities such as felling and cross-cutting of trees, log piling, stacking, and loading and unloading charcoal kilns. The same assumption as for the montane forest products was made about value of wood extracted for charcoal production.

3.2.4 Estimating carbon stocks in forests, woodlands, and agricultural lands

Data on carbon stocks in different pools of the two studied forest types (miombo and montane forest) and surrounding agricultural lands were obtained from various published sources (Table 5). Averages were taken when more than one estimate per vegetation type was available. A rough estimation of biomass was also made in the WMB area and the surrounding open woodland for comparison with the biomass data obtained from other miombo woodlands. Ten plots were sampled using an inventory design proposed by the National Forestry Resources Monitoring and Inventory of Tanzania and similar biomass densities were found in WMB as reported for miombo (Luoga et al. 2002). The below-ground biomass of miombo woodlands was estimated as 20 % of the above-ground biomass. The soil carbon of croplands in original miombo woodlands was estimated at 60 % of soil carbon in miombo woodlands (Walker and Desanker 2004). The carbon estimate was multiplied by the conversion factor of 3.67 to obtain tons of carbon dioxide equivalents (tCO_2). The net carbon or equivalent carbon dioxide that will be protected under the REDD+ scheme was estimated as the mean of the total carbon storage of each vegetation type minus the mean of the total carbon storage under the corresponding alternative land use (i.e., agriculture).

3.2.5 Data analysis

Of the 606 sample plots, 593 were used for analysis after the data were cleaned. The remaining plots were omitted from the analysis due to incomplete information (e.g., because crops had not been harvested). To avoid the problem of non-normality caused by the fact that profitability

Table 5 Distribution of carbon stock (Mg ha^{-1}) by carbon pool in different land-use categories in the lowland and highland agro-ecological zones in Tanzania

Agro-ecological zone	Land-use type	Above-ground biomass	Dead wood	Litter	Below-ground biomass	Soil	Total	Source[a]
Highland	Afro-montane forest (a)	222.0	11.0	13.0	54.0	295.0	595.0	(2), (7)
	Crop land (b)	3.3	0.1	0.3	0.9	123.0	127.6	(7)
	Net loss (a-b)						467.4	
Lowland	Dense miombo woodland (a)	20.0	–	–	4.0	78.5	102.5	(1), (3), (4), (5), (6)
	Degraded miombo woodland (b)	3.5			0.7	78.5	82.7	(4), (8)
	Cropland (c)	0.6				47.1	47.7	(6)
	Net loss (a–c)						54.8	
	Net loss (b–c)						35.0	

[a] Sources: (1) Chamshama et al. 2004; (2) Munishi and Shear 2004; (3) Munishi et al. 2010; (4) Ryan et al. 2011; (5) Shirima et al. 2011; (6) Walker and Desanker 2004; (7) Willcock et al. 2012; (8) Zahabu 2008

on many plots was low while profitability on a few plots was very high, a Kruskal–Wallis test was used to detect statistically significant differences in the median NPVs of crop production as well as the median compensation estimates between the two agro-ecological zones and among the study villages within the zones. Non-parametric multiple pair-wise comparisons between different parameters were made using Tukey's test and t tests, with a significance level of $\alpha=0.05$. The statistical software R version 3.0.1 (R Core Team 2013) was used for analysis and SigmaPlot version 11 (Systat Software Inc. 2008) was used for plotting.

3.2.6 Sensitivity analysis and elasticity estimation

The analysis in the base case scenario assumed a constant value for each parameter (crop yield, carbon density, prices of the different crop types, and discount rates). However, these variables may have changed over time, thus affecting the results of the analysis. Therefore, to assess the sensitivity of the base case results to changes in the most important parameters, a sensitivity analysis was conducted by making changes in key variables. Changes in discount rate and carbon stock value were considered in the analysis. Based on an assumption that the current discount rate (5.3 %) was quite low, we examined the effect of increasing the discount rate to 10 %. For the carbon stock, reductions and increases of up to 50 % were assumed. Changes in carbon stocks can be caused by fire, uncertainties in carbon stock estimates (Pelletier et al. 2012), or enhanced growth due to different forest management interventions. Moreover, we obtained the elasticity of results to changes in crop yield from an estimated production function.

4 Results

4.1 Agricultural rent

Figure 2 shows the interquartile range (IQR) of the NPV estimates of each crop type across each study village and each agro-ecological zone. The median NPV estimates varied greatly across crop types, regardless of the wage rates applied. Maize cultivated with vegetables yielded a significantly higher ($p<0.001$) median NPV in the highland villages, while sugarcane and rice yielded a significantly higher ($p<0.001$) median NPV in the lowland villages. Depending on the wage rates used, the median NPV estimates also showed variation between the two agro-ecological zones; when the positive wage rates were considered, the median NPV of all the major crops was significantly higher in the lowland zone compared to in the highland zone. However, when the zero wage rate was considered, the median NPV tended to be higher in the highland zone, albeit not significantly (Fig. 3). Similarly, a significant variation in median NPV values between the study villages in the highland zone was observed when only one of the positive wage rates was used (Table 6). However, in the lowland zone, the median NPV between the villages showed significant variation regardless of the wage rates applied (Table 6). The results of the non-parametric multiple comparisons also confirmed variations in the median NPV between villages within the same agro-ecological zone. In the highland zone, when either of the positive wage rates was used, the median NPV estimate for Nyandira was significantly higher compared to the other three villages. However, differences in the median NPV value between the three villages, Ng'ungulu, Tchenzema, and Vinile, were insignificant. When the zero wage rate was considered, the median NPV estimate did not show significant differences among the villages. In the lowland zone, regardless of wage rate used, the median NPV estimate was significantly higher for Kunke compared to for Maseyu and Mlimbilo.

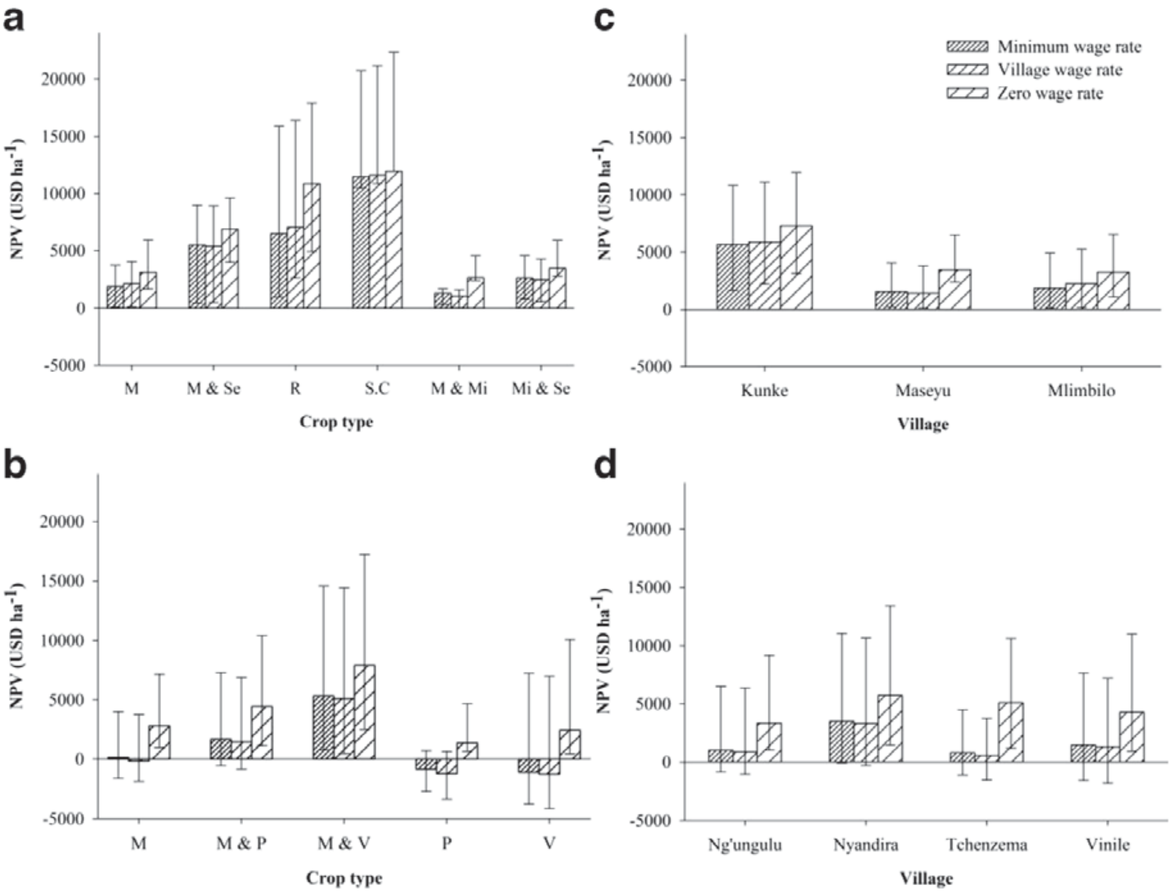

Fig. 2 The median NPV (USD ha^{-1}) of crop production by crop type (**a**, **b**), village (**c**, **d**) from the lowland zone (**a**, **c**), and the highland zone (**b**, **d**); the *lower* and *upper error bars* represent the first and third quartiles, respectively. *M* maize, *Mi* millet, *P* pulses, *R* rice, *S.C* sugarcane, *Se* sesame, *V* vegetables

However, the variation in the median NPV estimate for Maseyu and Mlimbilo was not significant. The difference in the NPV values (USD ha^{-1}) for the same crop types was also very high, with the IQR ranging between 884 for maize cultivated with millet and 14,380 for rice in the lowland zone, and between 3,207 and 13,324, respectively, for pulses and maize cultivated with vegetables in the highland zone. When the zero wage rate was considered, the IQR values showed a slight increase.

The different wage rates resulted in significantly different median NPV estimates for the major crops in all villages, except for Kunke (Table 7). Further, non-parametric multiple comparisons showed that the median NPV values estimated using a zero wage rate were significantly higher compared to estimates using both minimum and village wage rates. However, the minimum and village wage rates yielded similar median NPV estimates in both agro-ecological zones.

4.2 Forest rent

In the montane forest, the net returns per hectare from the different forest products during forest clearing was estimated to be USD 1,887 from poles, USD 262 from timber, and USD 160 from tool handles. The NPV of firewood collection was estimated as USD 1,797 ha^{-1}. The returns from the sustainable harvest were significantly higher compared to the returns from the other forest products during forest conversion. Table 8 lists the net returns from charcoal burning both during clearing and from annual sustainable harvest in the miombo woodlands.

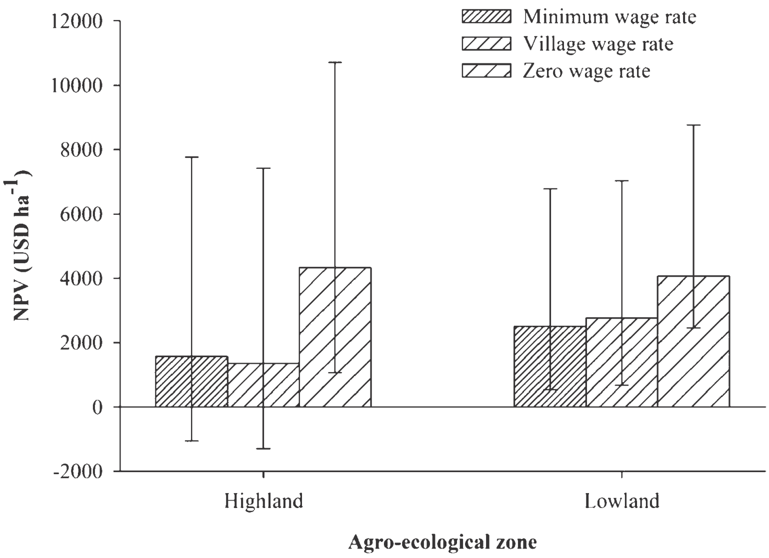

Fig. 3 The median NPV (USD ha^{-1}) of crop production in the highland and lowland zones; the *lower* and *upper error bars* represent first and third quartiles, respectively

The results shows that regardless of the wage rates used, NPV estimates of annual sustainable charcoal production for both the forest reserve and the public land resulted in a relatively higher value compared to the return from charcoal production during conversion. With regard to the wage rates, as in the case of crop production, the NPV values estimated by using the zero wage rate were found to be significantly higher than those estimated using the two other wage rates.

4.3 The OCs of stopping conversion of forestland to cropland

The net median income (USD ha^{-1}) that would be lost from not converting forestland into cropland was in the range of USD 1,289–6,277, depending on the wage rates considered (Table 9). With regard to village wage rate, both the lowest estimates (USD 2,289) and the highest (USD 5,006) estimates were observed in the lowland zone. However, when zero wage rate was used, the lowest estimate (USD 2,719) was observed in the lowland while the highest (USD 6,277) was in the highland (Table 9). The return from forest products during land clearing accounted for up to 16 % of the total median OC in the lowland zone and 70 % in the highland zone, depending on the wage rates considered and the biomass density of the miombo woodlands. When the village wage rate was used, the OCs from forest rent during forest conversion represented 64 % in the highland zone and 10 % in the lowland zone. The results also indicated that incentives from sustainable annual wood harvest could offset up to 45 % of the total median OCs of protecting the miombo woodlands in forest reserves and up to

Table 6 Variations in the median NPV of crop production between the study villages within the two agro-ecological zones

Agro-ecological zone	Minimum wage rate		Village wage rate		Zero wage rate	
	Kruskal–Wallis χ^2	*p* value	Kruskal–Wallis χ^2	*p* value	Kruskal–Wallis χ^2	*p* value
Lowland	15.17	<0.001	21.24	<0.001	16.44	<0.001
Highland	9.45	0.02	10.66	0.01	4.58	0.2

Table 7 Variations in the median NPV of crop production estimated using the different wage rates in each study village

Agro-ecological zone	Village	Kruskal–Wallis χ^2	p value
Lowland	Kunke	4.22	0.12
	Maseyu	18.18	<0.001
	Mlimbilo	5.73	0.049
Highland	Ng'ungulu	24.95	<0.001
	Nyandira	8.29	0.015
	Tchenzema	20.86	<0.001
	Vinile	20.74	<0.001

40 % for the miombo woodlands on public land, depending on the wage rates used. Similarly, the sustainable collection of firewood in the highland could offset about 55 % of the estimated total median OC with regard to the positive opportunity cost of labor.

4.4 REDD+ payments to offset OCs

The level of compensation required to reduce emissions of CO_2 by stopping the conversion of forestland to cropland differed significantly ($p<0.001$) in the two agro-ecological zones, and hence also for the different vegetation types, regardless of the wage rates used (Fig. 4); it was significantly higher in the study villages in the lowland zone. With regard to the village wage rate, the median compensation required to protect the current carbon stocks in the different vegetation types varied from USD 1 tCO_2^{-1} for the montane forest to USD 39 tCO_2^{-1} for the miombo on public land (Table 9). The zero OC of labor increased the median compensation value to USD 3 tCO_2^{-1} in the highland zone and to USD 43 in the lowland (Table 9). Regardless of the wage rate used, the median compensation estimates were also found to vary between villages within the same agro-ecological zones. When the village wage rate was considered, the median compensation ranged from USD 1 tCO_2^{-1} for Ng'ungulu, Tchenzema, and Vinile to USD 3 tCO_2^{-1} for Nyandira in the highland zone, and from USD 7 tCO_2^{-1} for Maseyu to USD 39 tCO_2^{-1} for Kunke in the lowland zone for the miombo woodlands on public land (Table 9). With regard to the zero wage rate, compensation estimates increased significantly, except for Kunke. With regard to the zero wage rate, when the compensation levels were calculated for each major crop separately, the variation in median compensation was high, ranging from USD 1 tCO_2^{-1} for crops cultivated in the highland zone to USD 81 tCO_2^{-1} for crops cultivated on formerly degraded miombo woodland in the lowland zone (Fig. 4). The OCs of avoiding cultivation of the most profitable crops after deforesting the

Table 8 NPV of charcoal production during forest conversion and through annual sustainable harvest

Legal status	Activity	NPV (USD ha^{-1})		
		Minimum wage rate	Village wage rate	Zero wage rate
Public woodland	Clearing	52	82	161
	Annual sustainable harvest	554	856	1,644
Forest reserve	Clearing	262	400	763
	Annual sustainable harvest	715	1,100	2,106

Table 9 Opportunity costs of stopping conversion of forestland into cropland and the required REDD+ payments to offset those costs

Vegetation type	Village	NPV (OC) (USD ha^{-1}) r=5.3 %			REDD+ payment (USD tCO_2) r=5.3 %		
		Minimum wage rate	Village wage rate	Zero wage rate	Minimum wage rate	Village wage rate	Zero wage rate
Dense miombo	Kunke	4,916	5,006	5,631	25	25	28
	Maseyu	1,824	1,363	2,860	9	7	14
	Mlimbilo	2,452	2,633	3,177	12	13	16
Degraded miombo	Kunke	4,866	4,932	5,490	38	39	43
	Maseyu	1,775	1,289	2,719	14	10	21
	Mlimbilo	2,402	2,559	3,036	19	20	24
Montane forest	Ng'ungulu	1,823	1,580	3,991	1	1	2
	Nyandira	4,791	4,660	6,277	3	3	4
	Tchenzema	1,965	1,482	5,397	1	1	3
	Vinile	2,287	2,067	5,156	1	1	3

relatively dense miombo woodlands were significantly higher compared to after deforesting the degraded miombo woodlands (Fig. 4).

4.5 Sensitivity analysis

When village wage rate is considered, an increase in discount rate from 5.3 % to 10 % can reduce the median compensation values by about 50 % in the lowland and by up to 30 % in the highland zone (Table 10). Similarly, a 10 % increase and reduction in carbon density can result in a 9 % increase and an 11 % reduction in the median compensation estimates, respectively. Moreover, the median compensations would increase by 100 % for a 50 % reduction in carbon density and decrease by 33 % for a 50 % increase in carbon density. The midpoint yield elasticity (0.274) of agricultural rent obtained from the production function showed that the results are not sensitive to changes in yield.

5 Discussion: implications for REDD+ implementation design

5.1 Agricultural rent

Variations in the median NPV were clearly related to crop types in both agro-ecological zones. We observed relatively higher median NPV estimates for villages with the highest percentage share of the most profitable crops. The reasons for choosing a certain crop type included agro-ecological considerations, distance to the nearest market, and farmland size. In Kunke, for example, sugarcane was the most profitable crop type cultivated on farmlands located close to the sugar factory; farmers able to grow sugarcane on 5 ha of land or more were able to sell their produce to the sugar factory. By contrast, rice, one of the most profitable crop types, is cultivated only in places with enough water, including Kunke and Mlimbilo but not Maseyu. In the highland zone, the continuous availability of water allows the local communities to cultivate vegetables (the most profitable crops in the highland villages) all year

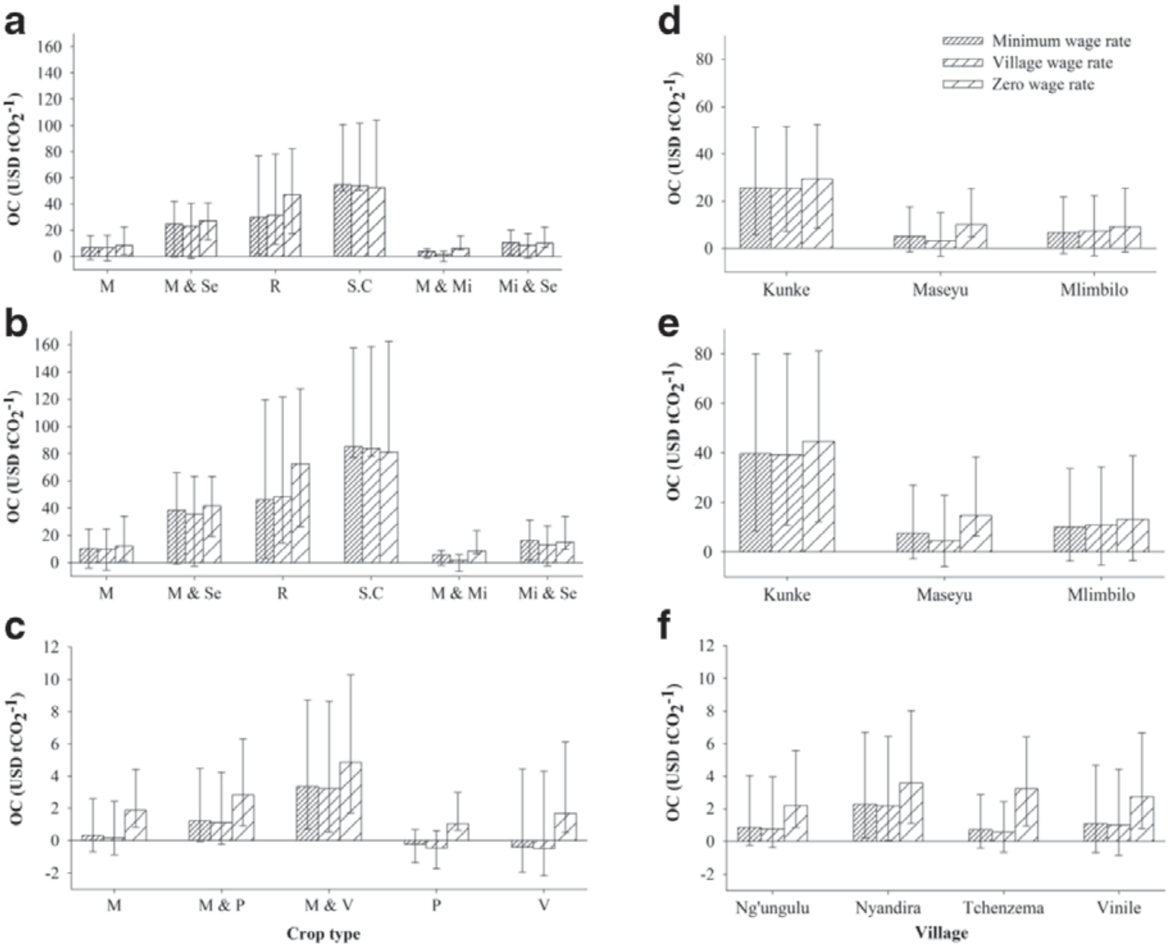

Fig. 4 The median compensation (USD tCO_2^{-1}) by crop type (**a**, **b**, **c**) and village (**d**, **e**, **f**) in the lowland (dense miombo) (*upper panel*), lowland (degraded miombo) (*middle panel*), and highland (*lower panel*); the *lower* and *upper error bars* represent first and third quartiles, respectively. *M* maize, *Mi* millet, *P* pulses, *R* rice, *S.C* sugarcane, *Se* sesame, *V* vegetables

round. However, in villages located farthest from the local market in Nyandira, such as Ng'ungulu, the cultivation of vegetables is limited.

Our analysis of agricultural rent showed a high variation in and a skewed distribution of NPV. The majority of farmers earned little income from the cultivation of crops, and only a few were able to make high profits. Hence, for a given REDD+ payment, normally a few families would still find it more profitable to continue to practice deforestation rather than accept the compensation and stop expanding their croplands. Few buyers would find it profitable to offer a sufficiently high price to convince the most efficient farmers to stop deforestation.

Labor input is an important component of crop production, and it can be broadly categorized into family labor and hired labor. Labor was abundant in the study villages, and the main source was family labor, particularly in the highland zone. Family labor accounted for more than 90 % of the total labor used in crop production in the highland zone and 70 % in the lowland zone. With the exception of Kunke, significant variation was found in all study villages in the median NPV of crop production between those estimated with regard to the positive OC of labor and those estimated using the zero OC of labor. The variation was higher in three villages in the highland zone because the main activities, such as land preparation, were undertaken using family labor. For some farm tasks that might require more labor, such as weeding, labor exchanges among relatives and neighbors were practiced. By contrast, in the lowland zone, particularly in Kunke and in some parts of Mlimbilo, some of the major tasks

Table 10 Results of the sensitivity analysis of REDD+ payments (USD tCO_2^{-1})

Vegetation type	Village	REDD+ payment (USD tCO_2^{-1})									
		Discount rate (*r*)		Carbon density (C)							
		r=10 %		+10 %		−10 %		+50 %		−50 %	
		Village wage rate	Zero wage rate	Village wage rate	Zero wage rate	Village wage rate	Zero wage rate	Village wage rate	Zero wage rate	Village wage rate	Zero wage rate
Dense miombo	Kunke	14	17	23	26	28	31	17	19	50	56
	Maseyu	4	9	6	13	8	16	5	10	14	29
	Mlimbilo	8	10	12	14	15	18	9	11	26	32
Degraded miombo	Kunke	20	23	35	39	43	48	26	29	77	86
	Maseyu	5	12	9	19	11	24	7	14	20	42
	Mlimbilo	11	13	18	22	22	26	13	16	40	47
Montane forest	Ng'ungulu	1	2	1	2	1	3	1	2	2	5
	Nyandira	2	3	2	3	3	4	2	2	5	7
	Tchenzema	1	2	1	3	1	3	1	2	2	6
	Vinile	1	2	1	3	1	3	1	2	2	6

were carried out by hired labor due to suitability of the area for using machinery such as tractors. The sugar factory took responsibility for harvesting on the sugarcane plantation. Our results show the significance of crop production in terms of providing employment opportunities for the villagers. The difference between the NPV values estimated using a zero labor cost and those estimated using a positive labor cost can be seen as foregone benefits in terms of lost employment opportunities. In places such as the areas in which the study villages were located, where there are no readily available alternative sources of income, forgone employment opportunities need to be considered when a REDD+ policy is designed. The availability of family labor together with the profitability of crop production, particularly in the lowland zone, implies that the villagers have possibilities and incentives for increasing their farm size wherever land is suitable. Further intensification of their high-value crops implies greater increases in the costs of implementing the REDD+ policy measure.

5.2 Forest rent

The results showed that sustainable wood harvests from the montane forest and from both dense and degraded miombo woodlands resulted in a significantly higher NPV compared to the net returns from wood harvest during conversion to croplands. This was due to the relatively low discount rate used in the NPV estimation.

5.3 The OC of stopping conversion of forestland to cropland

The income that would be lost during conversion is significant. The OC originating from wood harvest during land clearing was significantly higher in the highland zone, but it was offset by the relatively higher return from sustainable harvest in the zone. In the case of miombo woodlands, no difference in OC estimates was observed between the woodlands in the forest reserve and those on public land. The return from charcoal production during forest conversion was higher from miombo woodlands in the forest reserve compared to miombo woodlands on public land, mainly due to the relatively higher biomass density in the former case. However, since the return from sustainable harvest was also higher from miombo woodlands in the forest reserve than on public land, the OC was offset. The results also highlighted the significance of sustainable harvests in offsetting some of the OCs, depending on the biomass density of the vegetation. In places, such as the areas occupied by the study villages, where more than 90 % of the local people depend on biomass energy, such incentives might be more realistic and attractive to local communities than monetary incentives (Mohammed 2011). According to Kaczan et al. (2013), compared to cash payments, non-monetary payments in the form of fertilizers would motivate farmers' participation in reducing the degradation of forests of the Usambara Mountains in Tanzania. Consideration of such measures under the REDD+ scheme can be important in terms of minimizing OCs. However, depending on the forest products that are considered to be harvested sustainably, such incentives can also involve high management costs and therefore increase the implementation cost of the REDD+ policy. For example, in the studied villages, the firewood collected from the montane forest does not require much management input, but the harvesting of wood from miombo woodlands for charcoal production would require additional management costs if the harvesting were to be kept within sustainable limits.

5.4 REDD+ payments to offset OCs

The results of our analysis showed significant variation in the median compensation required to protect the different vegetation types in the two agro-ecological zones. Several researchers have noted variations in the OCs of emission reduction among tropical locations, depending on ecological and economic conditions (e.g., Grieg-Gran 2008; Strassburg et al. 2009). Further, Fisher et al. (2011) reported a variation (IQR=USD 3.20–5.50 tCO_2^{-1}) in the OCs of avoiding agricultural expansion and charcoal production between 53 districts in eastern Tanzania. In our study, the main difference in the OCs was attributed to variations in biomass (carbon) density between the two vegetation types, and between the miombo woodland in forest reserve and on public land. When labor was valued as cheap, the NPV (USD ha^{-1}) of agricultural production was not significantly different between the highland and lowland agro-ecological zones. However, due to pronounced differences in biomass density between the montane forest in the highland and the miombo woodland in the lowland zone, the OC per ton of CO_2 was significantly different. These findings support those of (Yamamoto and Takeuchi 2012), who have pointed out the significance of variations in carbon density due to vegetation and soil conditions for significant differences in REDD+ compensation estimates. Our estimates of REDD+ payments required to protect the montane forest are similar to estimates reported for humid tropical forests with equivalent carbon densities (e.g., Bellassen and Gitz. 2008; Yamamoto and Takeuchi 2012). However, our estimates for the miombo woodlands are higher than estimates of REDD+ compensation payments reported for other miombo woodlands. For example, Bond et al. (2010) estimated that the regional OC of avoiding the conversion of miombo woodlands to agricultural lands would range from about USD 2.5 tCO_2^{-1} for Namibia and Mozambique to USD 3.71 tCO_2^{-1} for Zambia. The differences in compensation estimates are due to variations in assumptions regarding time horizon, discount rate, and carbon density. For example, Bond et al. (2010) used a discount rate of 10 % p.a. and planning period of 30 years. The carbon density considered ranged from 45 to 60 tC ha^{-1}, which are between double and triple the carbon density used in our analysis. The net returns to cultivation reported are also significantly lower than the agricultural rents found in our study area.

The differences in estimated carbon payments between the villages within each agro-ecological zone were due to variations in the NPV estimates of crop production, which were attributed to differences in crop type. The highest value was observed for Kunke, mainly due to the relatively high profits from sugarcane and rice cultivation. Variations in compensation values due to differences in farming system (subsistence and cash crop cultivation) have also been noted by Bellassen and Gitz (2008) and by Olsen and Bishop (2009). During our study, we observed that the prices of sugarcane and rice were lower than elsewhere in Tanzania. Based on the information gathered from the growers, we anticipate that the prices of the crops will increase in the near future and may thus increase the profitability of cultivating these crops, which would imply that the potential change in the prices of some crops should be taken into account when designing a REDD+ policy.

Our results suggest that implementing a REDD+ policy may be feasible in the highland agro-ecological zone, where considerable emission reduction could be achieved for a payment of less than the current carbon price (USD 5 tCO_2^{-1}) in the European market (McGrath 2013). Regarding the miombo woodlands, we found that it would be comparatively cheaper to protect the denser miombo woodlands in the forest reserves than the more degraded miombo woodlands on public land. However, the implementation of the REDD+ policy in the lowland zone would generally require higher compensation payments. Further, the analysis was based on assumed carbon payments at stump, which means that the actual carbon payment might be higher than our estimates. Moreover, incorporating implementation costs which according to Fisher et al. (2011) are estimated to be USD 6.50 CO_2^{-1} on average would further increase the cost of the policy measure.

Our results suggest that implementing the REDD+ scheme may be feasible if the biomass (carbon) density in the studied vegetation is high. However, the relatively dense miombo woodlands and intact montane forest are currently protected as forest reserves, and the present REDD+ schemes do not distinguish official protection status of areas. Nevertheless, implementing REDD+ in the existing protected forests could be an effective and a feasible measure to cut CO_2 emissions, mainly for three reasons. First, deforestation and degradation is significant in protected areas. For example, between 1975 and 2000, 3.4 % of forest and 28.3 % of miombo woodland were lost from the EAM (Green et al. 2013). Currently, respectively 74 % and 32 % of the remaining forest and woodland in the EAM are within protected areas (Green et al. 2013). Coastal forests in protected areas have been declining too, at a rate of 0.2 % per year since the 1990s (Godoy et al. 2011). Similarly, miombo woodland in the KFR has declined by 6 % between 1964 and 1996 (Luoga et al. 2005). The statistics imply that law enforcement efforts alone have not been sufficient to protect Tanzania's forests, and therefore economic measures are required to enforce effective protection.

The second reason why implementing REDD+ in the existing protected forests could be an effective and a feasible measure to cut CO_2 emissions is that the available carbon density in protected forests and woodlands is relatively high compared to forests and woodlands on public land, and the third reason is that the total cost of establishing new forest reserves would be higher than maintaining the existing ones. The median annual actual and necessary management costs in the EAM are estimated to be USD 2.3 ha^{-1} (IQR=USD 1–6 ha^{-1}) and USD 8.3 ha^{-1} (IQR=USD 5–17 ha^{-1}), respectively (Green et al. 2012), and are much lower than USD 0.1 tCO_2^{-1}. Thus, implementation of the REDD+ policy could be an opportunity to help strengthen established protected areas. Given the fact that about 50 % of Tanzania's forests and woodlands are within forest reserves, it would be logical to invest in the existing reserves.

5.5 Sensitivity analysis

As with all land valuations, high discount rates imply lower land values, and in the case study also lower compensation levels. Given the level of poverty persisting in rural Tanzania, a discount rate of 10 % per annum may not be entirely unrealistic in estimations of OCs. Most inhabitants in areas of miombo woodland have a very low income and they often prefer immediate consumption, which means they have to apply high discount rates (Bond et al. 2010). In the case of the lowland agro-ecological zone, the increase in discount rate meant that the compensation level in Maseyu was reasonable. Similarly, the implementation of the REDD+ policy could be feasible in Maseyu if the carbon density of the dense miombo is 50 % higher than the density we gathered from secondary sources. On the other hand, a decrease of up to 50 % in the carbon density of the montane forest would not lead to a level where it would become infeasible to invest in reduced emissions, particularly when a positive wage rate is considered. A positive wage rate may be a realistic assumption in areas where rural people can find alternative employment.

6 Conclusions

Knowledge of the monetary incentives required to avoid or reduce deforestation and forest degradation in various areas under different settings can help to identify economically feasible locations for the implementation of the REDD+ policy. Our study estimated the financial incentives required to stop the deforestation of both the montane forest in the highland agro-ecological zone and the miombo woodlands in the lowland agro-ecological zone of Morogoro Region, Tanzania. The median compensation required to protect the current carbon stock in the two vegetation types ranged from US$ 1 tCO_2e^{-1} for the montane forest to US$ 39 tCO_2e^{-1} for the degraded miombo woodlands. Our analysis revealed that the level of compensation required to avoid the forestland from being converted into cropland depended mainly on the biomass (carbon) density of the vegetation to be protected. Variations in assumptions regarding the OCs of labor and discount rate resulted in significant variations in the OC estimates and hence also the compensation levels between the two agro-ecological zones and between villages within the same agro-ecological zone. In such places as where our study villages were located, where there are few employment opportunities to compensate farmers for the reduction in work as a consequence of implementing REDD+, the level of compensation should be relatively higher. The choice of crop types attributed to both agro-ecological conditions and market access is an important factor in determining the feasibility of the implementation of the policy measure. From our study, we can conclude that given all possible factors that can potentially affect estimates of REDD+ payments, it would be more feasible to implement the policy in the highland zone than in the lowland zone. Depending on the biomass density of the vegetation to be protected, sustainable wood harvesting could be an important incentive under the REDD+ scheme. Moreover, considering factors such as available biomass density, implementation and management costs, and the degree of existing deforestation, the implementation of the

REDD+ policy in existing protected areas could be a feasible and effective way to reduce emissions of CO_2.

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PAPER II

Long-term responses of maize yield and selected soil properties to deforestation and subsequent cultivation of miombo woodlands in Tanzania

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Abstract

The miombo woodlands of Tanzania have been, and continue to be subjected to deforestation and degradation. Knowledge of long term productivity of subsequent land use can help estimate long term returns to deforestation. This study uses both socioeconomic and soil survey data to assess maize yield and selected soil properties, respectively with increasing cultivation period since conversion from miombo woodland. Data on maize production was collected from 110 households and 94 plots in three villages, while soil sampling was undertaken on 15 plots in one of these villages. Soil samples were taken from protected miombo woodland and from croplands with a history of cultivation varying from 2 to 52 years. Samples were taken at 0–10 cm and 11–20 cm depth and analyzed for the major plant nutrients (N, P, and K), soil organic C (SOC), pH, bulk density and texture. According to the results of the socioeconomic analysis, continued cultivation of croplands on former miombo woodlands do not have a significant effect on maize yield. The results of the soil analysis showed that conversion of miombo woodlands to cropland, and subsequent continuous cropping, can have a temporary negative effect on SOC stock in the first 2–7 years of cultivation. Soil organic matter (SOM) in the lower soil layer also declined by 40 % after 52 years of cultivation. The major plant nutrients on farmlands in both soil layers, however, did not show a significant change from the adjacent miombo woodland and did not decline with increasing cultivation period. The fact that the woodlands are generally located on naturally nutrient poor soils, and that they were degraded prior to conversion into cropland, might explain why there was no significant negative effect on the soil quality, and thus on crop yield. This also indicates that the current farming system can maintain some of the major plant nutrients and thus productivity. This further implies that agricultural rent after deforestation of the miombo woodlands does not necessary decline over time.

Key words: Continued cultivation, Deforestation, Miombo woodlands, Plant nutrients

1 Introduction

Miombo woodland is a widespread vegetation type in substantial parts of sub-Saharan Africa, including Angola, Zimbabwe, Zambia, Malawi, Mozambique, Tanzania, and southern part of the Democratic Republic of Congo (Dewees et al. 2010). ‘Miombo’ is a vernacular name used to describe woodlands dominated by species of the genera *Brachystegia*, *Julbernardia* and *Isoberlinia* (Campbell 1996). The miombo region covers 2.4 million km^2 with about 75 million rural dwellers and additional 25 million urban people relaying on it (Dewees et al. 2010). The woodlands generally occur on nutrient-poor soils in areas that receive 650-1400 mm of annual rainfall. The soils in general have low contents of N and extractable P (Frost 1996). In Tanzania, these woodlands cover about 47 % of the total land area and about 93 % of the forest and woodland ecosystems (NAFORMA 2014). They have been, and continue to be subjected to deforestation and degradation. It is estimated that the country’s forests and woodlands have been declining at an average rate of about 1 % per year since the 1980s (NAFORMA 2014). Several studies have concluded that agricultural expansion and extensive wood extraction for charcoal making are two of the most proximate causes of deforestation in the country (Angelsen et al. 1999, Luoga et al. 2005, Lusambo et al. 2008, Nduwamungu et al. 2008, Kissinger et al. 2012). On the other hand, there has been a growing demand for environmental services such as carbon sequestration provided by tropical forests and woodlands owing to the recognition of payments for ecosystem services (PES). Sustainable and intensive agricultural production has been suggested as one way of limiting the expansion of agriculture, and thus deforestation. Therefore, understanding the relationship between deforestation and the dynamics of productivity of the subsequent land use is important for a sustainable management of forests.

The financial justification for deforestation in developing countries in general is because agriculture provides higher economic return than standing forests and woodlands. Alternatively, scientists argue that the profitability of deforested land is short-term, as the soil loses its fertility, and consequently its productivity, over time. Several studies (e.g. Lal 1998, Islam and Weil 2000, Zingore et al. 2005) showed that deforestation and subsequent land use for crop production in general leads to deterioration in soil chemical, physical, and biological properties. The rates of change, however, differ greatly both between and within farms (Haileslassie et al. 2005) depending on several factors such as inherent variation in soils, particle size distribution, type of cultural practices, and soil conditions prior to conversion. On the other hand, little effects of clearing and continuous cultivation on soil properties have also been reported. For example, Hati et al. (2006) observed that the SOC content in unfertilized plots did not change after 31 years of continuous cultivation. Improvements in plant available nutrients after conversion are also reported. For example, Lemenih et al. (2005) observed an increase in concentrations of exchangeable K and P in croplands cultivated for up to 53 years.

The aim of this study was to assess the long-term responses of maize yield and selected soil properties to permanent conversion of miombo woodland into cropland, with subsequent continuous cropping in a small-scale farming system, and thus to assess the long term returns to agriculture. Such information is required to evaluate the sustainability of the existing farming systems. In addition, it can help to predict the dynamics of agricultural production for better valuation of actual and potential returns to land use change. This further helps to provide information for the design of compensation based climate change mitigation measures such as REDD+ (Reducing Emissions from Deforestation and Degradation, enhancing forest carbon stocks, sustainable management and conservation of forests), which requires information on returns to alternative uses of forest land.

2 Materials and Methods

2.1 Study sites

Three villages, Kunke, Maseyu and Mlimbilo, in the Morogoro region in Tanzania were selected for this study (Figure 1). Kunke and Mlimbilo are located 120 km north of Morogoro town while Maseyu is located 50 km east of Morogoro town along the road to Dar es Salaam. The climate in the region is generally characterized as sub-humid tropical, with a mean annual rainfall ranging from 800 to 1200 mm (MRDO 2006). The rainfall has a bimodal distribution with the short rains falling from October to December and the long rains falling from March to June. The mean annual temperature ranges from 28 to 31 °C (MRDO 2006). The soils in the area vary according to topography and parent material. In valley bottoms, mollisols and inceptisols are dominating (Msanya et al. 1995). The parent material of the soils is neogene colluvium, derived from metasedimentary rocks rich in garnet-biotite gneisses with microcline and muscovite (Msanya et al. 2003). The mean annual soil temperature is categorized under *iso-hyperthermic* (> 22^{o}C) (Msanya et al. 2003). The vegetation type is generally characterized as open dry miombo woodland.

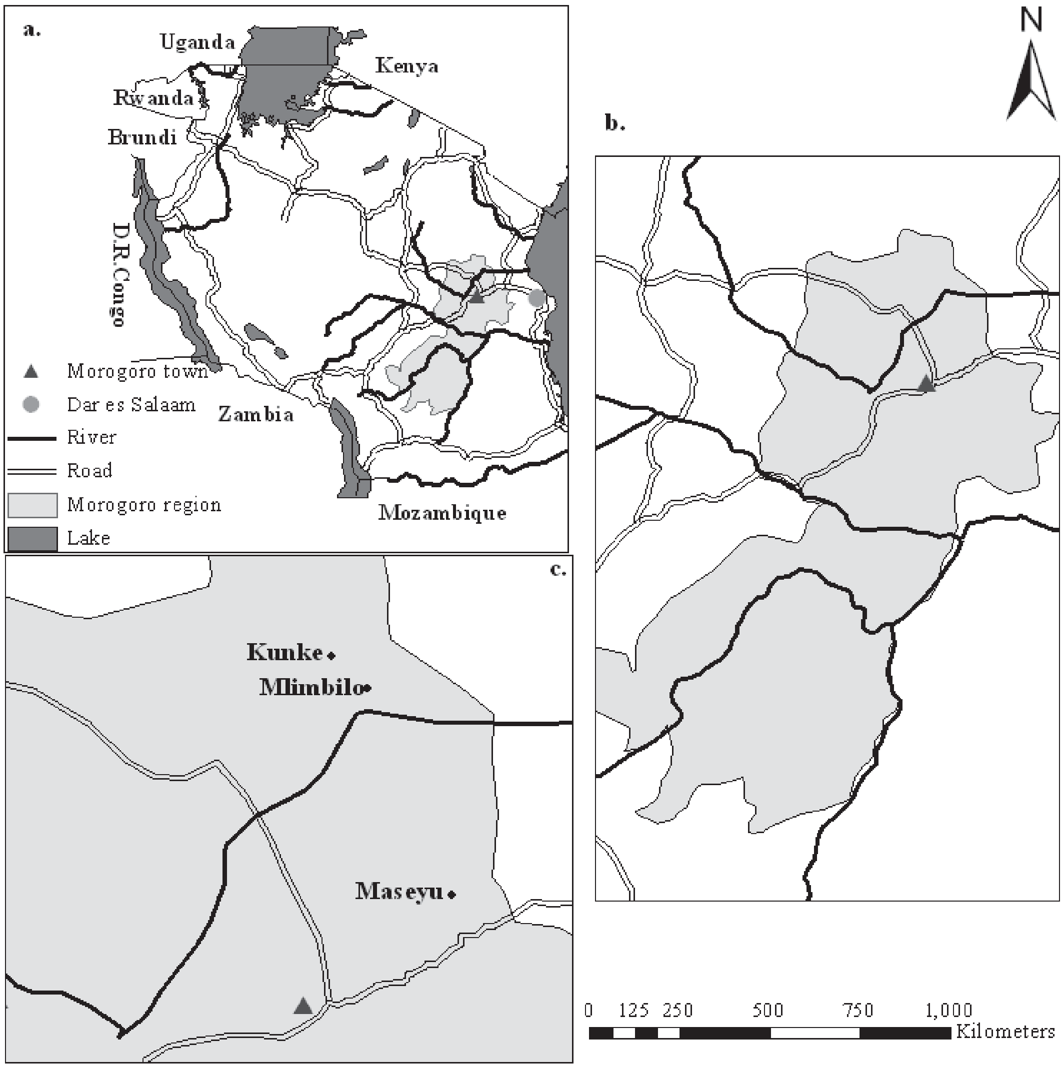

Figure 1. Map of Tanzania (a), Morogoro region (b), and the study villages (c).

2.2 Farming systems

The people in the three study villages depend mainly on small scale agriculture for their livelihoods. About 80 % of the inhabitants cultivate maize (*Zea mays* L.). Other crops include millet (*Eleusine coracana* L.) and sesame (*Sesamum indicum* L.). The size of farmlands ranges from 0.4 to 6.0 ha. The mixed farming system with permanent upland cultivation in the area integrates crops and scattered trees (Ruthenberg 1980). The most common tree species found in the croplands include mango (*Mangifera indica* L.) and cashew

(*Anacardium occidentale* L.). Site preparation usually involves the burning of herbaceous plants and crop residues. Soil fertility management in the study villages generally does not involve the application of commercial fertilizers, but animal manure is widely used. Livestock rearing is also a source of livelihood for some inhabitants, and free grazing is the common system practiced in the area.

2.3 Data and soil samples collection

The effect of continuous cultivation on land quality and productivity can be assessed by quantifying yields across farmlands with different cultivation periods, or by evaluating the condition of key indicators of soil quality such as SOC, soil pH, and available plant nutrient reserves under farmlands of different cultivation period (Lal 1998). In this study, data on both crop yield (maize) and selected soil chemical and physical properties were used to evaluate agricultural productivity in relation to the number of years the plots have been cultivated.

2.3.1 Socioeconomic survey

The socioeconomic data from the three villages were collected in January 2012. A total of 30 households were randomly selected from Kunke, 54 from Maseyu, and 37 from Mlimbilo. Basic demographic information, data on maize yield per hectare and characteristics of each farm plot were obtained using structured questionnaires.

2.3.2 Soil survey

The soil survey was undertaken in Maseyu only. The miombo woodland in this village has been subjected to continuous deforestation for more than 50 years. During the period between 1975 and 2000, the miombo woodlands have declined at an estimated annual rate of 1.7 %, while croplands and degraded woodlands with scattered croplands increased with an annual rate of 1.5 and 2.8 %, respectively (Nduwamungu et al. 2008). The soils of this site are described as well drained red sand clay loams with a pH ranging from 5 to 5.5 (Msanya et al. 1995). For this study, 12 closely located farmlands with more or less similar topographic, climatic and edaphic conditions, as well as management history, were selected. The farmlands had been cultivated from 2 to 55 years since conversion from miombo woodlands. When each farm was cleared for crop production was determined by interviewing the land owners and village administrators. An additional three sample plots were selected from miombo woodlands in the adjacent Kitulangalo forest reserve. This was done to detect possible changes due to the conversion and subsequent continuous cultivation of miombo woodlands.

Soil sampling - Soil sampling was done in November 2011, outside the cropping season. In each of the 12 plots on croplands and 3 plots on the miombo woodland, a 20 m * 20 m sampling plot was established. In each sampling plot, a total of five mini-pits, four at the corners and one at the center of the plot, were dug to a depth of up to 25 cm using a shovel. Soil samples were collected from one wall of each pit at two depths (0–10 cm and 11–20 cm). The five soil samples at each depth were mixed to get a composite sample. Each composite sample was placed in a labeled plastic bag and they were taken to the soil laboratory at the Sokoine University of Agriculture in Morogoro. The soil samples were air dried and sieved through a 2 mm sieve for chemical analysis. Another set of soil samples, for bulk density determination, were collected using a core sampler from the two above mentioned depths. The core samples for bulk density determination were oven dried to a constant weight at 105 ^{o}C.

Soil analysis - To measure soil pH, the samples were mixed with deionized water, with soil: water ratio of 1: 2.5 and pH was measured by placing a glass electrode in the mixture. Organic carbon was determined by the wet oxidation method of Walkley and Black (Nelson and Sommers 1982) and converted to organic matter by multiplying by a factor of 1.724. The Kjeldahl method (Bremner and Mulvaney 1982) was employed to determine total nitrogen. Available phosphorus was extracted by the Bray and Kurtz-1 method (Bray and Kurtz 1945) and it was determined using a spectrophotometer (Murphy and Riley 1962, Watanabe and Olsen 1965). Exchangeable potassium was extracted by saturating soil with neutral 1M NH4OAc (Thomas 1982) at a pH of 7, and the extracted potassium was measured with an atomic absorption spectrophotometer. Texture was determined in soil suspension by hydrometer method (Day 1965). Bulk density was determined using the core sample method (Blake 1965).

2.4 Data Analysis

2.4.1 Socioeconomic data

Agricultural yield was assessed along farmlands with different ages since conversion from miombo woodland. In addition to the important variable, cultivation period (age of a given plot), other factors (explanatory variables) thought to have both fixed and random effect on maize yield, were also considered in the analysis. Descriptions of the explanatory variables used in the analysis are summarized in Table 1. Only farmlands used for maize production were considered in the analysis. Consequently, the total number of farm plots used for this analysis was 94. Before analysis, explanatory variables were tested for correlation between each other. When two variables were strongly correlated, only one was considered in the analysis. A linear mixed-model was applied to examine the effect of the different explanatory variables on the response variable (maize yield). A reason for choosing a mixed-model was to be able to incorporate a random variable; in this case the administrative unit (village) into the model. In order to check if the model fits the data, a test for lack of fit was made. The statistical software, R version 3.0.1. (R Core Team 2013) was used for analysis.

2.4.2 Soil data

To compare the mean value of each soil parameter among cultivation periods, the cultivation period (age) of the plots was categorized into 4 groups; field plots cultivated for 1–10 years were grouped under category 1, 11–20 years under category 2, 21–30 years under category 3 and >30 years under category 4. The miombo woodland was considered as category 0. One way analysis of variance (ANOVA) was used to detect statistically significant differences in mean values of each soil parameter per depth among the different categories of cultivation periods. Pair-wise comparisons of means of each soil parameter per depth between the different cultivation period groups were made using Tukey’s studentized test. A significance level of $\alpha = 0.05$ was used. The statistical software, R version 3.0.1. (R Core Team 2013) was used for analysis and SigmaPlot version 11 (Systat Software Inc 2008) was used for plotting.

Soil organic C stock (SOC) (g m^{-2}) was calculated using the formula,

$$SOC = SOC * BD * D * 100$$

Where: SOC is the carbon stock in g m^{-2} of a sample depth, D, the depth of a sample layer (cm), BD, the bulk density in g m^{-3} of a sample depth D, and SOC, the carbon content in g $100g^{-1}$ soil of a sample depth. The same equation was applied to estimate the stock of total N (g m^{-2}) for each soil layer.

Table 1. Description of the response and explanatory variables used in the model

Variables	Description	Variable type	Number of factors (levels)	Effect
Response variable				
Yield (Yie)	Total yield harvested (kg ha^{-1})	Continuous		
Explanatory variables				
Village (Vil)	An administrative unit	Factor	3 factors	Random
Sex	Sex of the household head	Factor	2 factors	Fixed
Age	Age of the house hold head	Continuous		Fixed
Family size (FL)	Family member above 10 years old are considered in the analysis	Continuous		Fixed
Education (Ed)	Number of schooling years completed by the house hold head	Factor	3 factors	Fixed
Number of plots (NP)	Number of plots managed by the particular household	Continuous		Fixed
Ownership (OS)	If the farm manager has user right to the plot or rents from others	Factor	2 factors	Fixed
Plot size (PS)	Total area of a given plot	Continuous		Fixed
Distance from household (DHH)	Time required to reach to the plot from the user's house	Continuous		Fixed
Cultivation period (CY)	The time period since the land was being used for crop cultivation	Factor	4 factors	Fixed
Distance from the nearest forest (DF)	Distance in minutes walking to the particular plot from the nearest forest	Continuous		Fixed
Soli type (ST)	Soil texture based on the farm managers description	Factor	4 factors	Fixed
Land quality (LQ)	Land quality in terms of fertility according to the farm managers	Factor	3 factors	Fixed
Slop (Slo)	The degree to which the plot is exposed to erosion (slop of the farmland)	Factor	3 factors	Fixed
Degree of weed infestation (DW)	The degree to which the plot is affected by weed	Factor	4 factors	Fixed
Seed input (SI)	Amount of seed used per hectare	Continuous		Fixed
Labor input (LI)	Man days employed per hectare of land	Continuous		Fixed

3 Results

3.1 Maize yield and cultivation period

Figure 2 shows maize yields across farmlands of different age. The average yield per hectare was 1.19 ton (Figure 2). The results of the linear mixed model analysis showed that the number of years of continued cultivation of croplands on former miombo woodlands did not have a significant effect on maize yield. Of all the other explanatory variables included in the model, distance from household (DHH) and land quality (LQ) showed significant fixed effects on maize yield at 1 % and 5 % levels of significance, respectively (

Table 2). As expected, plots described as to have good quality, resulted in relatively high yields. Moreover, the further the plot was from the farm manager's house, the higher the yield. This can be explained by the frequency of disturbance in nearby plots, which might result in reduced yield. The test of lack of fit resulted in non-significant effects. This implies that the data can be fitted in the model but the explanatory variables, except the two, do not have a significant effect on the response variable. The reason why the other explanatory variables also did not show significant effect on yield can be that as the main aim of the study was to see the impact of cultivation period on yield; other factors such as the explanatory variables were controlled as much as possible. Hence, it is not surprising that most of the variables did not show significant effect on yield. With respect to the variable (village) thought to have a random effect, the variance of the variable was very low and thus it can be concluded that its effect was insignificant.

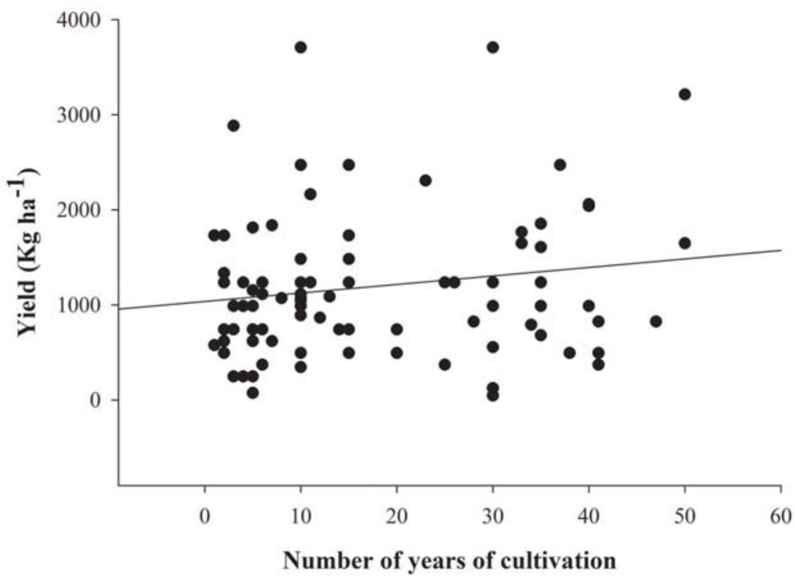

Figure 2. Observations of maize yield across farmlands of different cultivation age.

Table 2. ANOVA table of variables explaining variation in maize yield

Source of variation	df	SS	MS	F	Pr (>F)
Sex	1	1254948	1254948	2.209	0.141
Age	1	18745	18745	0.033	0.856
FL	1	221637	221637	0.390	0.534
Ed	2	610983	305492	0.538	0.586
NP	1	362213	362213	0.637	0.427
DHH	1	7641817	7641817	13.448	< 0.000***
CY	1	287360	287360	0.506	0.479
OS	1	585152	585152	1.030	0.313
DF	1	8750	8750	0.015	0.901
ST	3	2201571	733857	1.291	0.284
LQ	2	4492679	2246340	3.953	<0.05*
Slo	3	554817	184939	0.325	0.807
DW	3	251357	83786	0.147	0.931
PS	1	221993	221993	0.391	0.534
SI	1	30956	30956	0.054	0.816
LI	1	889139	889139	1.565	0.215

3.2 Soil chemical and physical properties responses to conversion and continuous cultivation

3.2.1 Soil chemical properties

Major plant nutrients (N, P and K) - The concentrations of the major plant nutrients, N, P and K, on the miombo woodland and on the croplands of different age categories, in both upper (0–10 cm) and lower (10–20 cm) soil layers are presented in Figure 3. The mean N in the miombo woodland was 0.24 ± 0.03 in the upper soil layer and 0.19 ± 0.03% in the lower soil layer (Table 3). In the croplands, it ranged between 0.23 ± 0.02 and 0.28 ± 0.02 % in the upper soil layer and between 0.19 ± 0.02 and 0.23 ± 0.04 % in the lower soil layer (Table 3). The variation in average N between the miombo woodland and the croplands was not significant. In the croplands, average N (%) in the lower soil layer declined with increasing cultivation period, but not significantly. In the upper soil layer however, a consistent trend was not observed.

Available P was generally higher in the croplands compared to in the miombo woodland. Average P in the woodland was 5.64 ± 0.27 mg kg^{-1} in the upper soil layer and 2.20 ± 0.20 mg kg^{-1} in the lower soil layer, while in the croplands it ranged from 19.15 ± 27.67 to 55.71 ± 6.06 and from 16.38 ± 25.69 to 44.38 ±13.22 in the upper and lower layers, respectively (Table 3). The variability in P within the cultivation period category was very high and there was no clear relationship between cultivation period and P concentration.

The average concentration of K on the miombo woodland was 0.65 ± 0.17 (cmoles kg^{-1}) in the upper soil layer and 0.35 ± 0.10 (cmoles kg^{-1}) in the lower soil layer (Table 3). In the croplands, it ranged between 0.81 ± 0.23 and 1.00 ± 0.17 (cmoles kg^{-1}) in the upper soil layer and between 0.46 ± 0.31 and 0.86 ± 0.07 (cmoles kg^{-1}) in the lower soil layer (Table 3). The average concentration of K in the lower soil layer was significantly higher ($P < 0.01$) on the croplands compared to the same soil layer in the miombo woodland. In the upper soil layer however, the variation in average K concentrations between the woodland and the croplands was not statistically significant. The variation in average K between the different age categories of croplands was also insignificant for both soil layers.

Soil organic matter (SOM) – In all age categories of the croplands, SOM in the upper layer was slightly higher than in the lower layer (Table 3). In the miombo woodland however, SOM was similar in both layers. In the upper soil layer, there was no significant variation in SOM between the miombo woodland and any of the four cultivation period categories. Similarly, the variation in SOM content among the cultivation period categories was not significant, in both upper and lower soil layers. In the lower layer, however, the highest SOM content (2.42 %) was measured in the miombo woodland, while the lowest (1.45 %) was observed in cultivation period category 4. The reduction in average SOM after up to 52 years of cultivation was 40 %.

Soil organic carbon and total nitrogen stocks - Total N and SOC stocks (g m^{-2}) in the 0-20 cm soil surface layer showed a similar trend except for in cultivation period category 4. Figure 4 shows that the highest mean SOC content (1836 g m^{-2}) was observed in the miombo woodland, while the lowest (1221 g m^{-2}) was found in cultivation period 1. It is shown that average SOC stock dropped by 33.5 % after 2–7 years of cultivation. The N content also declined by about 9 % within 10 years of cultivation. The highest was, however, observed in cultivation period 2 (309 ± 57 g m^{-2}) and 4 (304 ± 57 g m^{-2}). After reaching an equilibrium after about 20 years of continuous cultivation, SOC content continued to decline, although at low rates.

pH - The pH values of the miombo woodland and the croplands were not significantly different, in both soil layers. Similarly, pH values between cultivation period categories were not significantly different.

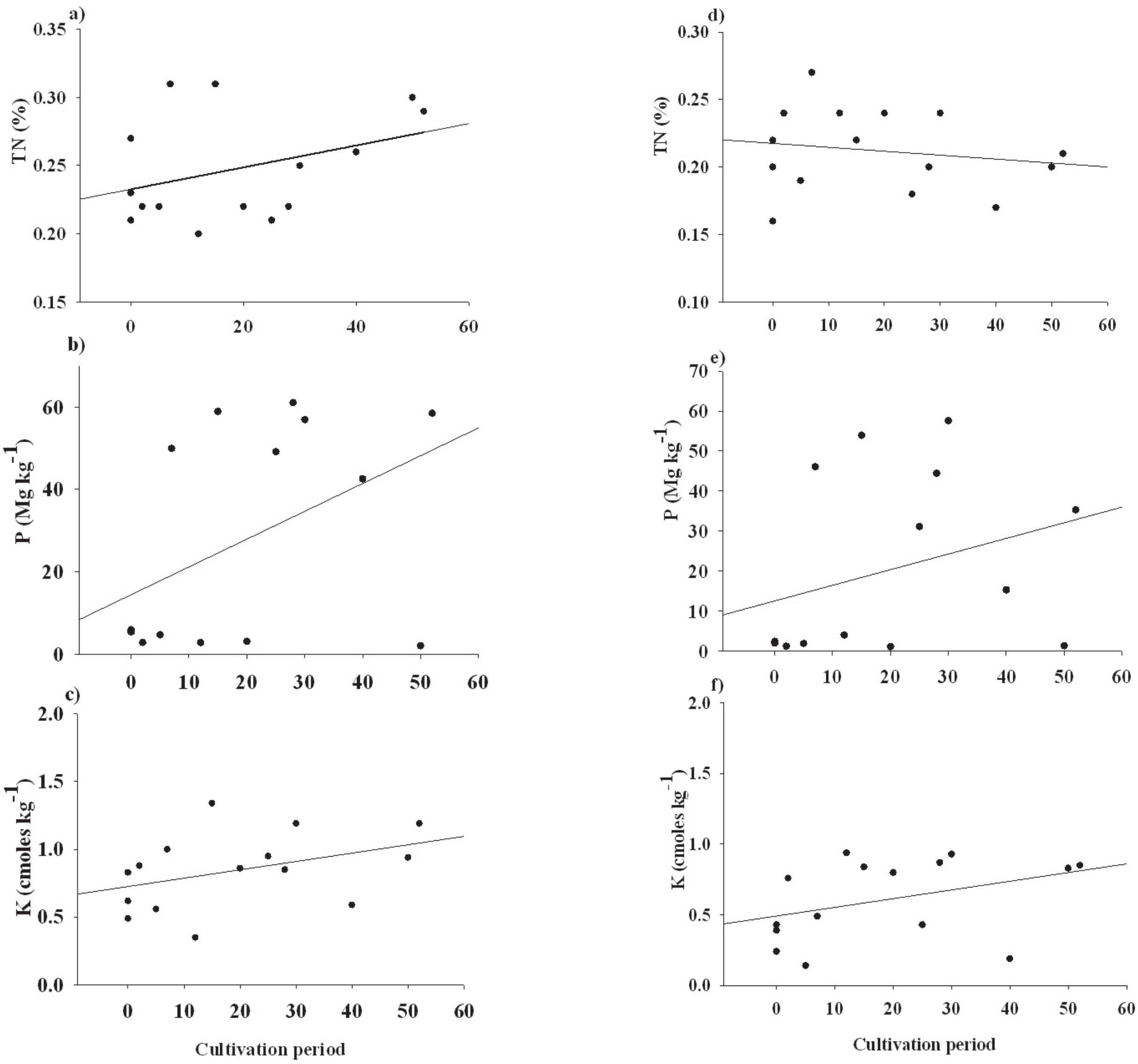

Figure 3. Observations of the major plant nutrients in the upper (0-10 cm) (left) and the lower (10-20 cm) (right) soil layers across cultivation period.

Table 3. Mean (± STD) for selected soil properties in the 0–10 cm and 10–20 cm soil layers on miombo woodland and across croplands of different cultivation period categories since conversion from miombo woodland

Soil parameter	Depth (cm)	Cultivation period 0	1-10	11-20	21-30	>30	ANOVA
Total N (%)	0-10	0.24 (±0.03)	0.25 (±0.05)	0.24 (±0.06)	0.23 (±0.02)	0.28 (±0.02)	
	10-20	0.19 (±0.03)	0.23 (±0.04)	0.23 (±0.01)	0.21(±0.03)	0.19 (±0.02)	
P (mg kg^{-1})	0-10	5.64 (±0.27)	19.15 (±27.67)	21.61 (±32.31)	55.71 (±6.06)	34.36 (±29.12)	
	10-20	2.20 (±0.20)	16.38 (±25.69)	19.68 (±29.72)	44.38 (±13.22)	17.31 (±17.07)	
K exchangeable (cmoles kg^{-1})	0-10	0.65 (±0.17)	0.81 (±0.23)	0.85 (±0.49)	1.00 (±0.17)	0.91 (±0.30)	
	10-20	0.35 (±0.10)	0.46 (±0.31)	0.86 (±0.07)	0.74 (±0.27)	0.62(±0.38)	
pH	0-10	5.79 (±0.49)	5.62 (±0.49)	5.58 (±0.77)	5.72 (±0.21)	5.73 (±0.63)	
	10-20	5.56 (±0.45)	5.38 (±0.41)	5.14 (±0.11)	5.67 (±0.30)	5.64 (±0.12)	
SOM (%)	0-10	2.53 (±0.83)	2.13 (±0.55)	2.62 (±1.22)	2.13 (±0.54)	2.53 (±0.89)	
	10-20	2.42 (±0.67)	1.84 (±0.30)	1.98 (±0.20)	1.87 (±0.60)	1.45 (±0.04)	
BD (g cm^{-3})	0-10	1.28 (±0.17)	0.99 (±0.18)	1.25 (±0.04)	1.29 (±0.15)	1.22 (±0.03)	*
	10-20	1.34 (±0.19)	1.17 (±0.09)	1.34 (±0.17)	1.28 (±0.21)	1.35 (±0.09)	
Sand (%)	0-10	65.53 (±6.66)	63.20 (±5.29)	49.53 (±10.69)	66.20 (±9.64)	62.87 (±10.12)	
	10-20	58.20 (±4.58)	64.53 (±8.33)	51.20 (±10.00)	64.20 (±4.58)	56.87 (±11.06)	
Silt (%)	0-10	20.37 (±4.65)	20.87 (±2.52)	27.03 (±5.84)	18.03 (±4.48)	22.07 (±7.92)	
	10-20	23.53 (±4.07)	19.53 (±4.04)	26.53 (±5.03)	20.20 (±3.61)	23.37 (±4.31)	
Clay (%)	0-10	14.10 (±2.29)	15.93 (±3.51)	23.43 (±4.85)	15.77 (±5.35)	15.07 (±2.34)	*
	10-20	18.27(±2.57)	15.93 (±4.93)	22.27 (±5.03)	15.60 (±1.00)	19.77 (±7.01)	

The values in parentheses are one standard deviation

Table 4. Soil organic carbon (SOC) % and stock and total nitrogen (Total N) % and stock

Cultivation period	Depth (cm)	SOC (%)	Total N (%)	SOC (gm^{-2})	Total N (gm^{-2})
0	0-10	1.47(±0.48)	0.24 (±0.03)	1835 (±394)	302 (±46)
	10-20	1.40 (±0.39)	0.19 (±0.03)	1837 (±324)	260 (±57)
1-10	0-10	1.24 (±0.32)	0.25 (±0.05)	1181 (±90)	241 (±20)
	10-20	1.06 (±0.17)	0.23 (±0.04)	1260 (±303)	272 (±45)
11-20	0-10	1.52 (±0.71)	0.24 (±0.06)	1892 (±895)	303 (±74)
	10-20	1.14 (±0.12)	0.23 (±0.01)	1538 (±243)	314 (±50)
21-30	0-10	1.24 (±0.31)	0.23 (±0.02)	1589 (±360)	292 (±19)
	10-20	1.08 (±0.35)	0.21(±0.03)	1340 (±214)	264 (±44)
>30	0-10	1.47 (±0.51)	0.28 (±0.02)	1802 (±676)	347(±29)
	10-20	0.83 (±0.02)	0.19 (±0.02)	1131 (±83)	262 (±42)

The values in parentheses are one standard deviation

3.2.2 Soil physical property

The results of the bulk density analysis showed a significant decline in the first 2–7 years of cultivation, but that it remained unaffected following deforestation and continuous cultivation in both of the soil layers.

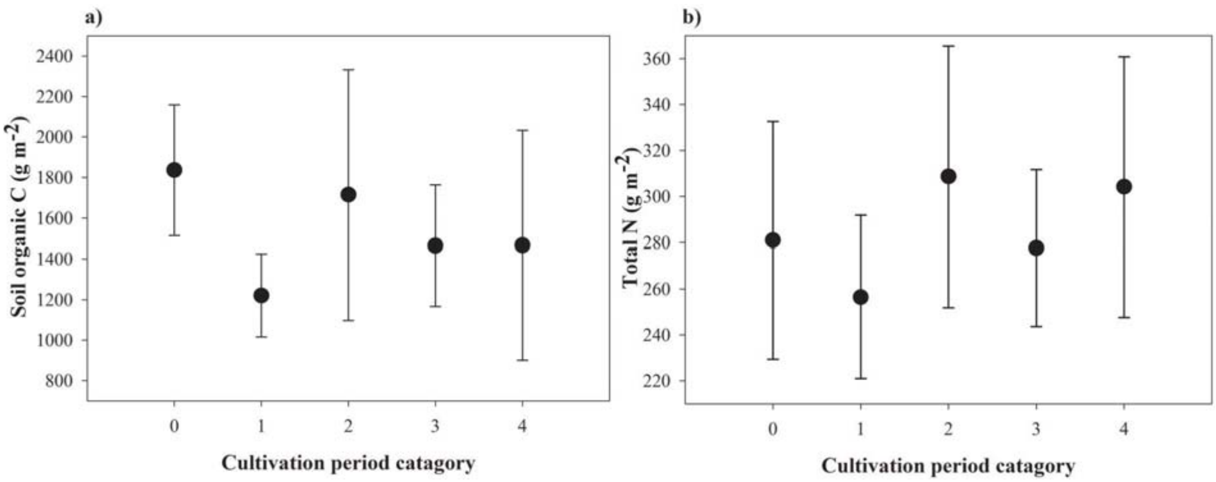

Figure 4. Organic carbon (a) and nitrogen (b) stocks in soil in different categories of cultivation periods after deforestation. 0: woodland, 1: cropland cultivated for 1–10 years, 2: cropland cultivated for 11–20 years, 3: cropland cultivated for 21–30 years, and 4: cropland cultivated for more than 30 years. The error bars represent one standard deviation

4 Discussion

4.1 Maize yield and number of years of cultivation

The development of agricultural yields after deforestation is a crucial factor in the long-term analysis of whether the conversion of forestland into cropland has been economically beneficial. This is independent of whether the loss of biodiversity and/or the emission of greenhouse gases during deforestation is included in the analysis or not. If agricultural yields are high in the first years immediately after deforestation, but then fall as a result of nutrient depletion, the decision to clear the forest may seem rational in the short run, but not in the long run. In such cases, deforestation may be profitable at high interest rates, but not if the interest rate is sufficiently low. In this study, no such trend of decreasing yields was found, since the studied woodlands are usually degraded prior to their conversion into cropland. This might explain why continuous cultivation did not show a significant negative effect on the yield. It can also be explained by the common farming practices in the area. By applying animal manure, annual burning, and keeping trees in the cropland, farmers evidently manage to keep maize yields stable long after the woodland was cleared.

4.2 Soil chemical and physical properties responses to conversion and continuous cultivation

Generally, a depletion of soil nutrients due to permanent conversion and subsequent continuous cultivation of miombo woodlands was not observed in this study. This is contrary to other studies, which have reported soil nutrient declines following deforestation and subsequent continuous cultivation (Lal 1998, Haileslassie et al. 2005, Kimaro et al. 2007, Abegaz and van Keulen 2009)

4.2.1 Soil chemical properties

Major plant nutrients (N, P and K) – The results regarding K and P from this study are comparable to those of Lemenih et al. (2005) who observed higher concentrations of exchangeable K (cmoles kg^{-1}) and P (mg kg^{-1}) in croplands cultivated for up to 53 years in comparison with soils in tropical dry Afro-montane forest, at both 0–10 cm and 10–20 cm soil depths. Clearing of miombo woodland and subsequent continuous cropping did not show a significant negative change in the major plant nutrients. This can be explained by the fact that the woodlands are generally located on soils naturally poor in nutrients, particularly in N and extractable P. Significant nutrient depletion usually occurs in soils with an initial high nutrient content (Zingore et al. 2005, Abegaz and van Keulen 2009). On the other hand, the relatively higher concentrations of the major plant nutrients in the croplands compared to the miombo woodland, could be attributed to the current farming system. Animal manure and other organic wastes are important sources of N. Moreover, substantial amounts of organic matter and plant nutrients can be added from the burning of plant material on the farmlands. Litter addition from on-farm trees can also be significant.

Soil organic matter (SOM) – SOM decreased with depth as expected, however, insignificantly. This is consistent with other studies (e.g. Haile et al. 2008, Gelaw et al. 2014). SOM in the upper soil layer of the miombo woodland was similar to that of the croplands of all age categories. It was also similar across the cultivation period categories. This can be related to the slow decomposition rate of litters in the miombo woodlands, due to low initial available N contents (Mtambanengwe and Kirchmann 1995). SOM in the lower soil layer of the miombo woodland was higher compared to the croplands of all age categories, although insignificantly. The result also showed signs of decline in SOM in the lower soil layer of the croplands due to clearing and continued cultivation. The rate of change was however, low due to probably their lower initial content.

Soil organic carbon and total nitrogen stocks – The decrease in the contents of SOC and N in the early cultivation years can be explained by the high intake of available nutrients by crops. In the croplands, relatively higher mean stocks of SOC and N were observed in cultivation period category 3 (10–20 years). This could be related to the clay content which was particularly high in that category. The SOC and N stocks after 20 years of cultivation showed a declining trend, except for category 4, where the N content was similar to that of category 3. Reduction in SOC and N contents due to continued cultivation is well documented. For example, Tiessen and Stewart (1983) showed 34 % and 29 % net loss in SOC and N, respectively, after 60 years of cultivation. Similarly, Abegaz and van Keulen (2009) reported about a 41% reduction in SOC after 50 years of cultivation in small-holder agriculture in the highlands of northern Ethiopia.

4.2.2 Soil physical property

The BD in the miombo woodland and the croplands of all age categories did not differ. Walker and Desanker (2004) also reported insignificant variations in bulk density between agricultural land and miombo sites in the upper 20 cm of soil. In general, BD on the lower layer was higher than in the upper layer except for cultivation period category 3 in which the BD in the upper and lower layer was the same. This may be due to the relatively higher SOC in the upper layer compared to in the lower, and higher compaction in the lower due to the absence of cultivation and mass of the soil above. The relatively low BD in croplands cultivated for up to 10 years, in which SOC was low, is probably due to tillage effects. BD of soil depends greatly on the degree of compaction. Forests and woodlands are expected to have relatively low BD compared to croplands. But, this was not the case in this study. This can be explained by the high level of compaction caused by cattle in the woodland.

4.2.3 Implications of the soil analysis results for maize yield

There are many factors affecting crop yield in general, and maize in particular. The amount of necessary available plant nutrients is one of the most important factors determining crop yield. Maize growth demands about 360–600 mg kg^{-1} of available K, over 6 mg kg^{-1} of available P, and a pH range of 5.8–8. Moreover, an N level and SOM contents of above 0.2 % and 2.0 %, respectively, are considered as good indices for N availability (Lemenih et al. 2005). The results of the soil analysis showed that the current available P is sufficient to support maize yield across all plots. Similarly, the N level, SOM contents and pH values in all of the croplands are within the required level. The current available K in all the croplands except those cultivated for up to 20 years is also satisfactory to support maize. This implies that the decline in some soil nutrients due to continued cultivation does not necessarily mean that the farmlands will not be able to support maize growth.

5 Conclusion

The results of both socioeconomic and soil analysis confirmed that clearing of miombo woodland and subsequent cultivation by small-scale subsistence farmers did not lead to a significant decline of maize yield and the most important soil nutrients, respectively. Overall, the current farming system, which incorporates few trees in the croplands, fertilizing using manure, and burning herbaceous plants prior cultivation and leaving crop residues in the plot after harvest can maintain and even increase some of the major plant nutrients. Besides, given the initial soil nutrients status of the miombo woodlands which is low, nutrient depletion is also low. This shows that deforestation of miombo woodlands in the study areas has been and still may be a transition from one sustainable (unless woodlands are degraded) situation to another (mixed cropping). This further implies that in areas like the study sites, returns to agriculture does not fall over time due to continuous cultivation and subsequent nutrient depletion.

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Paper III

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Optimal wood harvest in miombo woodland considering REDD + payments — A case study at Kitulangalo Forest Reserve, Tanzania

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ABSTRACT

Models for optimal management of forests and woodlands are important for designing climate change mitigation strategies. Biomass measurements from eight plots in Kitulangalo Forest Reserve, Tanzania, were used to estimate a Verhulst growth model for miombo woodland. After incorporating the effect of fire, a non-linear programming model was used to determine economically optimal harvest of such woodland for charcoal production. Optimization was done with and without payment for reduced emissions from forest degradation under the assumption that the woodland was not reserved for environmental protection. It helped testing strategies for management of public land. At the current charcoal price and discount rates above 7.3%, immediate harvest of present stock was found optimal. At 10% interest rate, carbon sequestration payments and emission taxes of 15 USD $MgCO_2e^{-1}$ were required so as to avoid woodland degradation. If emissions were not taxed, sequestration payments of more than 40 USD $MgCO_2e^{-1}$ would not prevent harvest when biomass density is high (60–100 $MgCO_2e$ ha^{-1}). The farm-gate price discussed here will be lower than the price found in international agreements due to transaction costs. Unless affluent societies are prepared to pay more than 10–20 USD $MgCO_2e^{-1}$, degradation of miombo woodlands in Tanzania and other sub-Saharan countries is likely to continue in the absence of some alternate measures.

1. Introduction

Miombo woodland is a common vegetation type in large parts of sub-Saharan Africa (Campbell, 1996). It extends from Angola in the west, through southern Democratic Republic of Congo into Mozambique in the East, and from Tanzania in the North to Zimbabwe in the South. The miombo region covers an estimated 2.4 million km^2 with about 75 million inhabitants and with an additional 25 million urban people relying on it (Dewees et al., 2010). The woodlands provide a wide range of goods and services, of which fuel wood is the most important for the urban dwellers (Campbell, 1996). The woodlands are generally characterized as deciduous, and they are dominated by 'miombo', a vernacular name for species of the genera *Brachystegia*, *Julbernardia* and *Isoberlinia*. In Tanzania, these woodlands cover about 90% of the forest and woodland ecosystems (Malimbwi et al., 2005), occupying 36% of the total land area. The woodlands are extensively used for fuel wood and charcoal making (Luoga et al., 2005; Monela et al., 1993; Nduwamungu et al., 2008). Wood harvesting rates in miombo woodlands commonly exceed increment rates (Ryan et al., 2012), particularly in areas that are easily accessible, and can be used profitably to supply bioenergy for urban consumption (Ahrends et al., 2010; Hofstad, 1997; Luoga et al., 2005). Degradation of miombo woodlands is often the result of wood harvesting as well as overgrazing and clearing for shifting or permanent cultivation (Campbell and Byron, 1996; Leach and Mearns, 1988; Luoga et al., 2000a).

Extraction of wood is an important aspect of woodland use alongside animal husbandry (Lund and Treue, 2008; Schaafsma et al., 2012). Management of woodland may, of course, be based on traditional knowledge and rough estimates of bio-physical variables. More precise analysis depends on better estimates of both stock and flow variables. The central stock variable is biomass or standing volume of trees, while the corresponding flow variable is current increment. Measuring of standing volume or biomass in miombo goes at least 30 years back (Stromgaard, 1985; Temu, 1981). Allometric equations for estimation of volume or biomass of individual trees for species prevalent in miombo woodlands are now readily available (Henry et al., 2011; Hofstad, 2005; Mugasha et al., 2013). Yield estimation is much more uncertain, however. Growth equations for miombo woodland or for individual trees in this vegetation type are still hard to come by. Since growth rings are hard to detect, and also irregular in such species, re-measurement of trees on permanent sample plots is the only practical, though cumbersome, way of collecting data for growth modeling. The lack of good yield models is a problem for planners and managers who would like to estimate allowable cut or non-decreasing harvest levels. It is also problematic for assessment of deforestation and degradation which has become essential for analysis of climate change mitigation (Kohl et al., 2009). This study therefore aims at developing a simple growth model for miombo woodland which is

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further used for optimization purpose. The second part of the paper investigates optimal harvest level in miombo woodland considering REDD + payments (payments to reduce emission of greenhouse gases from deforestation and forest degradation as well as afforestation to sequester greenhouse gases).

2. Materials and methods

2.1. Study site

Kitulangalo Forest Reserve (KFR) is located about 50 km east of Morogoro town and 150 km inland from Dar es Salaam, along the Dar es Salaam–Morogoro highway (Fig. 1). The reserve was originally established as a 'productive reserve' in 1985, with the aim of controlled utilization of the woodland. It covers an area of 2452 ha including the Kitulangalo hill (Luoga et al., 2002). In 1995 however, the reserve was closed for any kind of use (Luoga et al., 2002). The climate of the area is tropical, with mean annual rainfall ranging between 800 and 1200 mm, spread over 5–6 months (November to May) and a dry season extending from June to October. The mean annual temperature varies between 28 and 31 °C. The main vegetation type is open dry miombo woodland dominated by *Julbernadia globiflora*, *Brachystegia boehmii* and *Pterocarpus rotundifolius* tree species (Luoga et al., 2000a, b). The first two of these species are mainly used for charcoal making. According to the district office, there are about 4640 inhabitants in the surrounding three villages Lubungo, Maseyu and Gwata. The inhabitants are highly dependent on the surrounding protected and unprotected woodlands, for both domestic (firewood, fruit and vegetables, and timber and poles) and commercial use (charcoal). An estimated 1.2 m^3 ha^{-1} and 6.4 m^3 ha^{-1} of wood is harvested annually from the reserve and surrounding public woodland (Luoga et al., 2002). Next to agriculture, charcoal production is the main source of livelihood for the surrounding communities (Nduwamungu et al., 2008).

2.2. Growth modeling

Forest increment can be modeled in various ways; as a stand with site characteristics, forest density, and average height as input variables

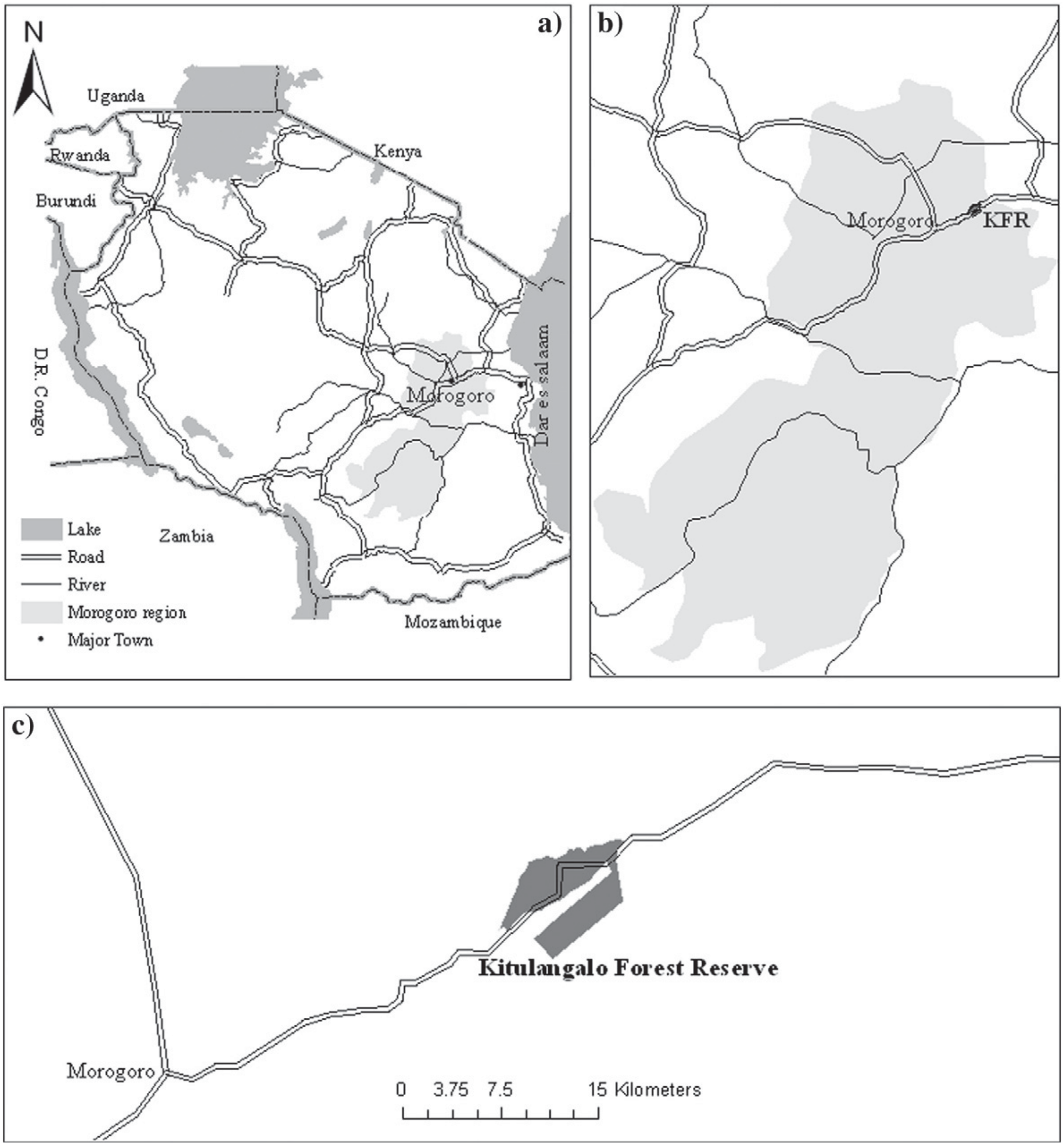

Fig. 1. Map of Tanzania (a), showing the location of Morogoro region (b), and Kitulangalo Forest Reserve (c).

(Moser, 1972), matrix model with diameter distribution as the main input (Liang and Picard, 2013), models of individual trees with competition indexes as important input (Vanclay, 1994), and as process models where ecological factors determining growth are the fundamental input variables (Makela et al., 2000). The simplest growth model, the Verhulst (1838) equation, relates increment of a homogenous natural resource to the resource density in a certain environment. This equation has been applied to a number of very different biological resources (Renshaw, 1991) and is widely used in economic analysis (Brander and Taylor, 1998; Clark, 1990; Guerrini, 2010).

2.2.1. Data

Data from eight permanent sample plots in the forest reserve were used to estimate a Verhulst equation for miombo woodland. The reserve was chosen because it is one of a very few miombo locations with long time series of biomass density observations. The plots were established by Kielland-Lund (1982) in 1977 and re-measured in 1978, 1990, 1992 and 1993 (Ek, 1994). Diameter and height of all trees were measured on 25 × 25 m square plots. Above ground woody biomass was estimated from diameter at breast height (D) and total height (H) using the allometric function: $B = 0.06\ D^{2.012}H^{0.7}$, where B is biomass density (Mg ha^{-1}) (Malimbwi et al., 1994). Observations of biomass density at different times are given in Table 1.

Since current increment was modeled, only growth intervals of one and two years were used. Biomass change from 1990 to 1992 was divided by two. There are three growth intervals for each of the eight plots giving 24 potential observations of growth. Three of these are negative (Table 1). Ek (1994) reported that reduced biomass density on plots 6 and 7 from 1977 to 1978 was caused by fire. The reduction on plot 4 from 1990 to 1992 was also caused by fire as well as by illegal harvest of firewood. Consequently, only 21 observations could be used for estimation of the growth function.

2.2.2. Model development

The Verhulst equation was chosen to describe biomass increment a priori because of its proven validity in biological growth modeling. While we are waiting for more detailed growth models for site classes, diameter classes or individual trees, this type of equation is the best model available. Even if more detailed models become available the Verhulst equation may be useful in many aggregated analyses because of its mathematical simplicity. The equation represents the relationship between the stock, S, and the growth, $\dot{S}$, of biomass in the woodland: $\dot{S} = a\,S - b\,S^2$, where a and b are positive constants.

The constants a and b were estimated by fitting a linear regression model using a statistical software, R version 3.0.1 (Stowell, 2014). The response variable (increment) was subjected to Shapiro–Wilk normality test before the model was fitted. An alternative mixed effect model was also considered to detect whether characteristics of individual plots have a random effect on the response variable. The two models were compared using R^2. We used fitted versus residual plot (a constant variance test) (Crawley, 2007) to evaluate the selected model.

Table 1
Biomass density (Mg ha^{-1}) in the eight plots in KFR observed over five different years.

Year	Plot number 1	2	3	4	5	6	7	8
1977	90.2	39.3	64.9	66.8	60.1	47.8	27.3	32.9
1978	93.0	42.2	67.2	72.0	67.2	44.5	15.9	34.4
1990	122.9	63.7	94.6	98.1	98.7	31.8	21.8	31.4
1992	127.4	73.6	105.1	96.1	104.5	34.9	23.3	34.2
1993	131.1	77.4	112.0	101.8	109.3	38.2	24.4	34.7

Source: Ek (1994).
Note: Cells showing negative change are shaded gray.

The p-value for the Shapiro–Wilk normality test was 0.364 showing that the response variable is normally distributed. Parameter estimates of the model and statistics of their fit are presented in Table 2. Both coefficients were significantly different from zero. The difference between the two models was not significant. Therefore, the first model was considered. The plot of fitted versus residual values showed no bias and a constant variance with p-value 0.469. Observations and the estimated growth function are shown in Fig. 2. Maximum stock of biomass, or carrying capacity, is $K = a/b$, which for $a \approx 0.0915$ and $b \approx 0.0005$ means that maximum biomass density in KFR is about 195 Mg ha^{-1}. Natural mortality is equal to gross increment, and net increment is zero.

Under normal circumstances there are fires occurring in miombo woodlands every dry season. Since observations on plots affected by fire were excluded from our material, fire must be considered afterwards if a realistic prediction of miombo growth is the aim. It can be found from Barbosa et al. (1999) that the average probability that a plot in wetter Zambezian woodland miombo burns in a particular year is approximately 0.37. Ryan and Williams (2011) reported that 5–6% of live trees (dbh > 5 cm) were killed in fires in miombo woodland. Since small trees are more likely to die in a fire, the reduction in live biomass is probably smaller. Multiplying 0.37 by 0.05, we find that predicted biomass in year $t + 1$ is reduced by 1.85% when fire is considered.

2.2.3. Projections for present management regime

The average biomass density in KFR in the year 2000 was 47 m^3 ha^{-1} (Luoga et al., 2002). This is equivalent to 40 Mg ha^{-1} using a 0.85 conversion factor from volume (m^3) of fresh wood to biomass (ton) (Malimbwi et al., 1994). Starting with this biomass density, we may predict the development of biomass for a variety of harvest rates by using the growth function developed above. The simplest case is to assume that there is no harvest or fire in the reserve. This presupposes that there is full compliance with the ban on harvesting, and that there is no fire (manmade or natural). Since we have not been able to verify the estimated growth function with independent data, a sensitivity analysis was made by subtracting or adding one standard error of both estimated growth parameters a and b (Table 2) from/to the mean value. We assumed errors of estimated parameters to be correlated since maximum biomass density observed on one plot in Kitulangalo was 281.6 Mg ha^{-1} (331.3 m^3 ha^{-1}) (Malimbwi et al., 2000). The results are shown in Fig. 3a. Projections beyond 30 years seem highly uncertain.

Man made fires may be reduced considerably by strict control, but there may still be some natural fires during the dry season. We included a scenario of the most likely fire occurrence similar to what was observed by Barbosa et al. (1999). However, Luoga et al. (2002) estimated annual wood removal to be in the order of 1.12 ± 0.68 m^3 ha^{-1} inside the reserve. Using the same conversion factor as the above, this corresponds to 0.95 ± 0.578 Mg ha^{-1} yr^{-1}. Therefore, we also included a scenario with both fire and the mean harvest rate. We assumed future harvest to be constant each year. This gave three biomass trajectories shown in Fig. 3b.

In the absence of harvest or fire, biomass density increases from present stock (40 Mg ha^{-1}) to its maximum in about 80 years. If the most likely present level of fire and harvest (0.95 Mg ha^{-1} yr^{-1}) is maintained, maximum stock will be 140 rather than 195 Mg ha^{-1} resulting from the pure growth model without fire or harvest. Long-term steady states represent a tripling from today's level of carbon stored in the woodland, but carbon density will still be considerably lower than what can be found in more humid forest vegetation in Tanzania (Munishi and Shear, 2004).

In the second part of the paper we used the estimated growth function to analyze optimal harvesting policies in miombo woodlands. Optimal harvest plans are considered with or without REDD + payments for carbon sequestration or carbon storage (emission reduction from reduced degradation).

Table 2
Parameters and statistics of estimated growth function.

Parameter	Estimate	Standard error	P-value
a	0.09147	0.0165	<0.001
b	0.00047	0.0002	0.010

2.3. Optimization problem

2.3.1. Economics of wood exploitation

In addition to de jure and de facto scenarios based on present institutional arrangements in KFR, we were interested in determining the optimal harvest rate in miombo woodlands that are used solely for fuel wood production, or for a combination of wood production and carbon sequestration or storage. Although some wood is removed from miombo woodlands for household consumption as firewood in rural areas, major quantities of harvested wood are used for charcoal production. This is due to the ease of transportability of charcoal and the high demand for it in urban centers. Consequently charcoal has a clear market price as opposed to firewood. For these reasons we assumed that all harvested wood is used for charcoal production. Charcoal producers earn a little more than the worth of their labor, and cost of other inputs in the production is minimal. Even the wood is normally free of charge since the licensing system is far from effective. We used three prices for a bag of charcoal (50–53 kg): 1) the actual price of charcoal (5 USD/bag) in 2011, 2) the current price of charcoal minus the cost of labor to produce it (2.3 USD/bag), and 3) a price higher than the current level (set at 10 USD/bag) assuming that future restrictions on forest utilization could potentially push the price of charcoal upwards.

To determine the optimal steady state growth of miombo woodlands in accordance with the Verhulst equation, one also needs the appropriate discount rate. Under the assumption of constant charcoal price, a real discount rate is required. The nominal rate of lending by the Bank of Tanzania as of January 2011 was 12% p.a. and the inflation rate from January 2010 to January 2011 was 6.4% (BOT, 2011). Accordingly, a rate of 5.3% p.a. was used for discounting. Since the time preference of charcoal producers may be higher due to their relative poverty, we also used a discount rate of 10% p.a. to see the sensitivity of results dependent on the discount rate.

Under these assumptions the optimality condition is (Johansson and Lofgren 1985): $d\dot{S}/dS = r$, where: r is the discount rate. The derivative of the Verhulst equation with respect to biomass density is: $d\dot{S}/dS = 0.09147–0.00094\ S = 0.053$.

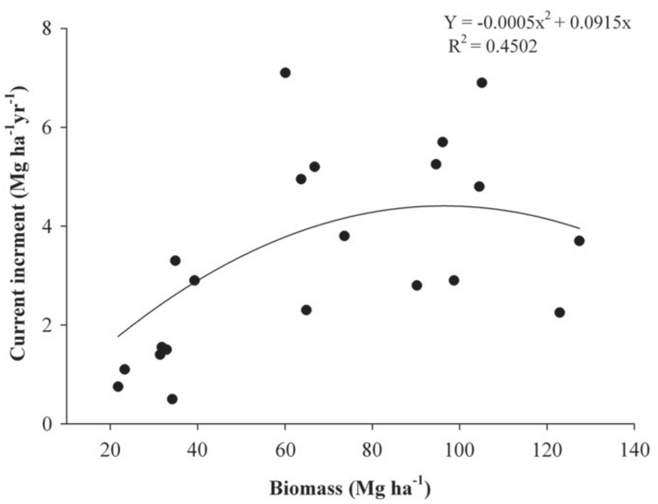

Fig. 2. Observations of current increment and biomass density in KFR, with an estimated Verhulst growth function.

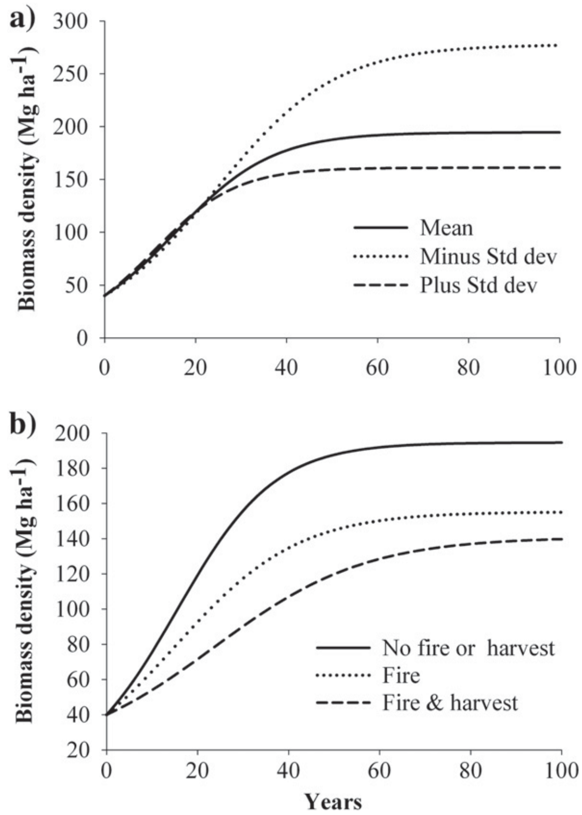

Fig. 3. Development of biomass density in KFR. In panel a) the model was used without fire or harvest, but with one standard error of both growth parameters subtracted or added to the mean values. In panel b) the mean parameter values of the model were used without fire or harvest, with fire alone, and with both fire and constant harvest of 1.12 $m^3\ ha^{-1}\ yr^{-1}$.

For $r = 0.053$ the optimal plan would be to keep a stock of 38.96 Mg ha^{-1} and harvest an even flow of 2.78 Mg $ha^{-1}\ yr^{-1}$ till infinity. Present value of annual harvests of 2.78 Mg ha^{-1} at a discount rate of 5.3% works out to 52.4 Mg. For discount rates above 7.3% the optimal plan would be to harvest all biomass immediately.

2.3.2. Economics of carbon sequestration

In order to reduce emissions of greenhouse gases it has been suggested that people in developing countries should be paid to grow trees or for not cutting existing ones (Schelling, 1992). It is prohibited to harvest wood in KFR. Therefore, no individual or organization receives payments to stop harvesting in this reserve. However, there are large areas of miombo woodland elsewhere in Tanzania and sub-Saharan Africa that are not included in nature reserves. In the absence of local growth functions for these areas we shall use the Verhulst equation from KFR to illustrate the effect of payments for reduced emissions from deforestation and forest degradation (REDD+).

Deforestation is a reduction of forest area. Here we are only interested in optimal management of the forest and not in the decision to use forest land for other purposes. Therefore, we only study the effects of payments to reduce forest degradation. Initial proposals to implement REDD + included a so called baseline (Chomitz, 2002), meaning that direct agents of deforestation should be paid if they reduce emissions below the business-as-usual scenario (Engel et al., 2008). Much has been written about the estimation of such baselines and suitable models for predicting business-as-usual emissions (Brown et al., 2007). However, a simple method has not yet been agreed upon. The estimation of baseline emission from forest and woodland degradation may prove to be even more complicated than that from deforestation.

In principle there are two ways to pay for reduced emissions of greenhouse gases due to forest degradation; 1) for carbon sequestration, or

2) for carbon storage. As put by Cacho et al. (2013), the first method "represents a purchase of carbon flows … whereas the later involves a rental of carbon stocks". REDD + payments could be related to a relative increase in biomass, or to a given biomass stored over a certain time period. Fig. 3 shows how biomass density would increase in miombo woodland similar to that found in KFR if no wood harvest took place. After about 60 years there would be no further biomass accumulation and no further carbon sequestration, requiring no further payments for sequestering it. To avoid degradation beyond this period, some other incentives would be required, e.g., rental of carbon storage, or a tax on emissions.

2.3.3. The model

A nonlinear programming algorithm was used to study a theoretical system where forest owners are paid according to changes in biomass density. They receive an amount proportional to an increase in biomass density. They may or may not pay an amount proportional to a biomass reduction. Payments are made annually.

The model may be expressed as a set of Eqs. (1) to (4):

Biomass growth:

$$S(t+1) = \left[(1+a)S(t) - bS(t)^2\right] - f\,S(t) - H(t) \quad (1)$$

a 0.09147, $b = 0.00047$
f mean expected rate of biomass loss due to wildfire = 0.0185
$S(t)$ biomass stock of trees in period t with $S(0) = 40$
$H(t)$ biomass harvested in period t.

Charcoal net revenues:

$$CR(t) = \varepsilon P_c H(t) \quad (2)$$

ε efficiency parameter, quantity of charcoal output per ton of biomass input (5 bags/ton)
P_c net price of charcoal (2.3, 5 or 10 USD/bag).

Sequestration net revenues:

$$SR(t+1) = 0.5 \cdot 3.67 \cdot P_s[S(t+1) + B(t) - S(t)] \quad (3)$$

P_s farm-gate price of sequestered CO_2 (USD Mg^{-1})
$B(t)$ baseline biomass reduction in period t.

Carbon content in woody biomass = 0.5.
Weight of CO_2 relative to C = 3.66667.
Objective function:

$$\max_{H(t)} NPV = \sum_{t=0}^{T}[CR(t) + SR(t)](1+r)^{-t} \quad (4)$$

T planning horizon
r real discount rate (% p.a.).

The objective function is maximized subject to Eqs. (1)–(3).

The model was run with different values for P_s, $B(t)$, and r. Parameter ε was kept constant under the assumption that the efficiency of carbonization is unlikely to change much in the coming 30 years. For CO_2, P_s, the prices of 0 to 40 USD $MgCO_2e^{-1}$ were used. In public woodland surrounding KFR, Luoga et al. (2002) found that harvest exceeded mean annual increment by approximately 2 m^3 ha^{-1} yr^{-1}. Two m^3 of wood is approximately 1.7 Mg of biomass and about 4.3% of the current stock. Therefore, two different approaches were used to baseline degradation, $B(t)$. For the first approach, a constant value of zero was used throughout the planning period, i.e., no reduction of biomass density would be accepted and only increases would be paid for. In the second approach we set $B(t) = 0.043\,S(t)$. This meant that baseline degradation would be 4.3% reduction in the stock each year. Consequently, any development with less than 4.3% reduction of biomass density would be paid for. We also applied two alternative policies of taxing woodland degradation. In the first case, Eq. (3) was applied without modification. This implied that a tax was levied on reduction of biomass density beyond the baseline. In the second case Eq. (3) was modified with an "if–then–what" statement such that no tax was levied on degradation, but biomass change above the baseline would result in a positive payment to the forest "owner". For discounting purposes, two constant annual rates of 5.3 and 10% were used as explained above. Planning period was fixed to be 30 years, since anything happening after 30 years is of very little importance when discounted at interest rates above 5%, and predictions of biomass development beyond that horizon may not be reliable. The model was run for 32 years, but only reported the first 30 years since the last couple of years were strongly influenced by the terminal conditions. The Solver algorithm for the Microsoft Excel spreadsheet program was used to run the model.

3. Results

The optimal solution was different for each model scenario. When there is no payment for carbon sequestration (REDD+), at any discount rate above 7.3%, immediate harvest of all biomass is the best economic solution regardless of the price of charcoal. This shows that if payment for carbon sequestration and storage is not taken into account, interest rate is the important factor in determining optimal harvest levels.

Fig. 4 shows optimal woodland management for different values of CO_2 price and discount rates when the sequestration contract includes tax of emissions, i.e., payment for reducing biomass density. When baseline degradation, $B(t)$, was zero, i.e., no biomass reduction is accepted, payments were only made for increasing biomass density. For the current price of charcoal (5 USD bag^{-1}) and interest rates between 5 and 10%, 15 USD $MgCO_2e^{-1}$ is required to stop wood harvesting. In this case, given the price of charcoal, price of CO_2 plays an important role in determining the optimal harvest level. The role of interest rate in determining optimal harvest level is significant when the price of CO_2 is relatively low and at early stages of the planning period. As the price of CO_2 increases, the effect of interest rate becomes less important over time. As illustrated by the case of 5 USD $MgCO_2e^{-1}$ and 10% interest rate (and the case without REDD payment at 5.3% interest rate), the combination of low (or no) REDD payment and high interest rates makes immediate harvest of large parts of available biomass the optimal economic solution.

Fig. 5 shows how optimal solutions depend on the price of charcoal. If the minimum wage multiplied by labor input was deducted from present charcoal price, the net value of one bag of charcoal became as low as 2.3 USD. With this as the basis for optimization, a CO_2 price of 10 USD $MgCO_2e^{-1}$ would be sufficient to stop wood harvesting completely. If shortages of charcoal supply (e.g. as a consequence of REDD + interventions) push the price up to 10 USD bag^{-1}, higher CO_2 prices will be required to reduce or stop wood harvesting. For a given price of CO_2, the role of interest rate in determining optimal harvest level becomes significant as the price of charcoal increases.

When baseline degradation was assumed to be 4.3% of the biomass stock, payments were made for increasing biomass density as well as reduced degradation. Changing the value of $B(t)$ for $t \in [0, T]$ from zero to

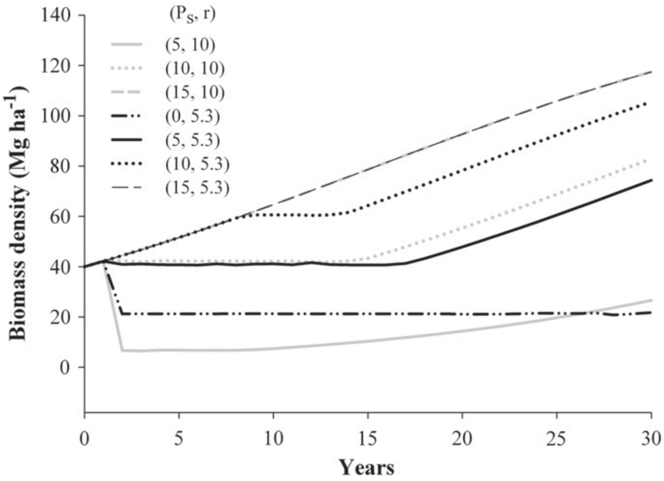

Fig. 4. Development of biomass stock, $S(t)$, over a 30 year period for two discount rates (5.3 & 10% p.a.) and different payments for carbon sequestration, P_s (0, 5, 10, and 15 USD $MgCO_2e^{-1}$). Charcoal price is 5 USD bag^{-1}, and no baseline degradation. REDD + contract includes tax on biomass reduction.

4.3% of biomass stock at each period led to some changes in the solutions to the management problem. For the current price of charcoal, the CO_2 price required to stop wood harvesting was slightly lower than the price required if baseline degradation was zero, regardless of the interest rate. However, this doesn't imply that it is cheap to stop wood harvesting if payment for baseline degradation is considered.

Fig. 6 shows optimal management strategies for different values of CO_2 price and discount rates, when baseline degradation is considered. Two alternative formulations of the sequestration contract are modeled. The first formulation does not include any tax on emissions, i.e., no payment for reducing biomass density. The second include a tax equal to the CO_2 price. In the first case this means that the forest owner receives a payment every year for which the biomass density increases proportional to the increase, but neither receives nor pays anything in years with reduction in biomass density. If the contract is formulated in this way, wood harvesting is an optimal solution whenever there is a relatively higher biomass density. This holds true regardless of the price of CO_2, as well as the interest rate. When baseline degradation is considered in the calculations of sequestration payments, a relatively higher biomass density can be maintained throughout the planning period than when there is no baseline degradation included in the contract.

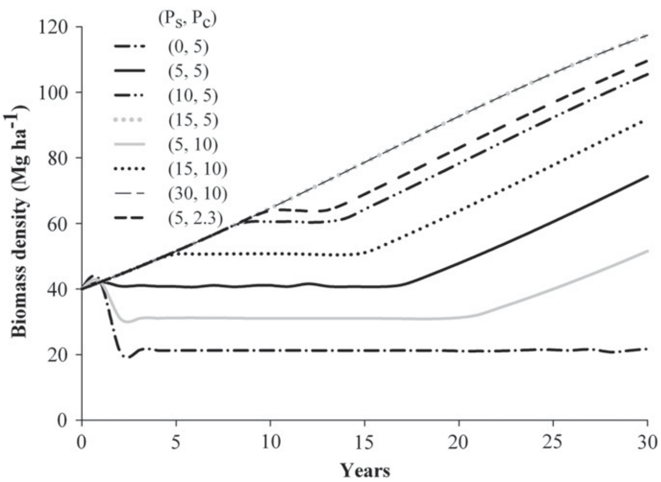

Fig. 5. Development of biomass stock, $S(t)$, for different prices of CO_2 (P_s) and charcoal (P_c). Prices in USD $MgCO_2e^{-1}$ and USD bag^{-1} are indicated in the legend. 5.3% discount rate.

4. Discussion

The Verhulst equation for biomass growth in miombo woodland estimated here can be useful in situations where knowledge of species and size distribution of trees is not important. From scattered practical experiences the equation looks reasonable, but we were unable to find any scientific data that could be used to test the reliability of the equation. Therefore, the equation should be considered a preliminary attempt at quantifying the relationship between biomass density and biomass increment in miombo. It may not be very reliable for long-term predictions of biomass development. Further progress in this field is likely in the years to come.

This study showed that price of CO_2 required for stopping miombo woodland degradation ranges between 10 and 40 USD $MgCO_2e^{-1}$ depending on several factors. If the estimated growth function underestimates actual biomass accumulation, higher prices are required, and the vice versa. In general, this price range is higher than what has been paid for emission quotas in the EU market (Zhang and Wei, 2010) from 2010 onwards, with recent low prices (USD5 $MgCO_2e^{-1}$) caused by economic recession in some European economies (McGrath, 2013). It is also higher than some estimates of CO_2 price required to stop deforestation in the tropics (e.g. Bellassen and Gitz, 2008). The required investments for developing baselines and certifying carbon offsets are likely to limit the participation of small landholders in the carbon market directly. Therefore, there will be a need for mediators who may pool a number of individual landholder contracts into a 'carbon project' (Cacho et al., 2013). This implies that the farm gate price will be considerably lower than the price of USD 5 $MgCO_2e^{-1}$ agreed on in large international contracts, like those between Norway and Brazil or Guyana (Amazon-Fund, 2008; GRIF, 2011). Therefore, either rich emitters in the North have to pay a higher price for CO_2 than in these initial contracts to avoid degradation of miombo, or miombo woodland is not a priority vegetation type for projects aimed at reducing emissions from forest degradation. It may be cheaper, in terms of CO_2 price, to reduce emissions from forests with higher biomass density than those from the open woodlands like the miombo. Fig. 6 shows that when there is no punishment for reducing biomass density, it is optimal to keep lower stocks and harvest more. This implies that in addition to higher payments for carbon sequestration and reduction of emissions from reducing forest degradation, a functioning institution responsible for monitoring and fine/tax collection may be required. This highlights the role of additional implementation costs.

5. Conclusion

The results of this study have strong implications for management decisions concerning carbon sink projects in the miombo woodlands. This study showed that the CO_2 price required to avoid miombo woodland degradation is higher than what has either been paid for emission quotas in the EU market or predicted for the tropics. In addition, management of these woodlands is likely to involve implementation and transaction costs. Hence, it can be concluded that, if parties are not prepared to pay more than 10–20 USD $MgCO_2e^{-1}$, degradation of miombo woodlands in Tanzania and other sub-Saharan countries is likely to continue unless other measures, such as, land tenure reforms, forest protection, and agricultural policies (Brown et al., 1993) are also undertaken.

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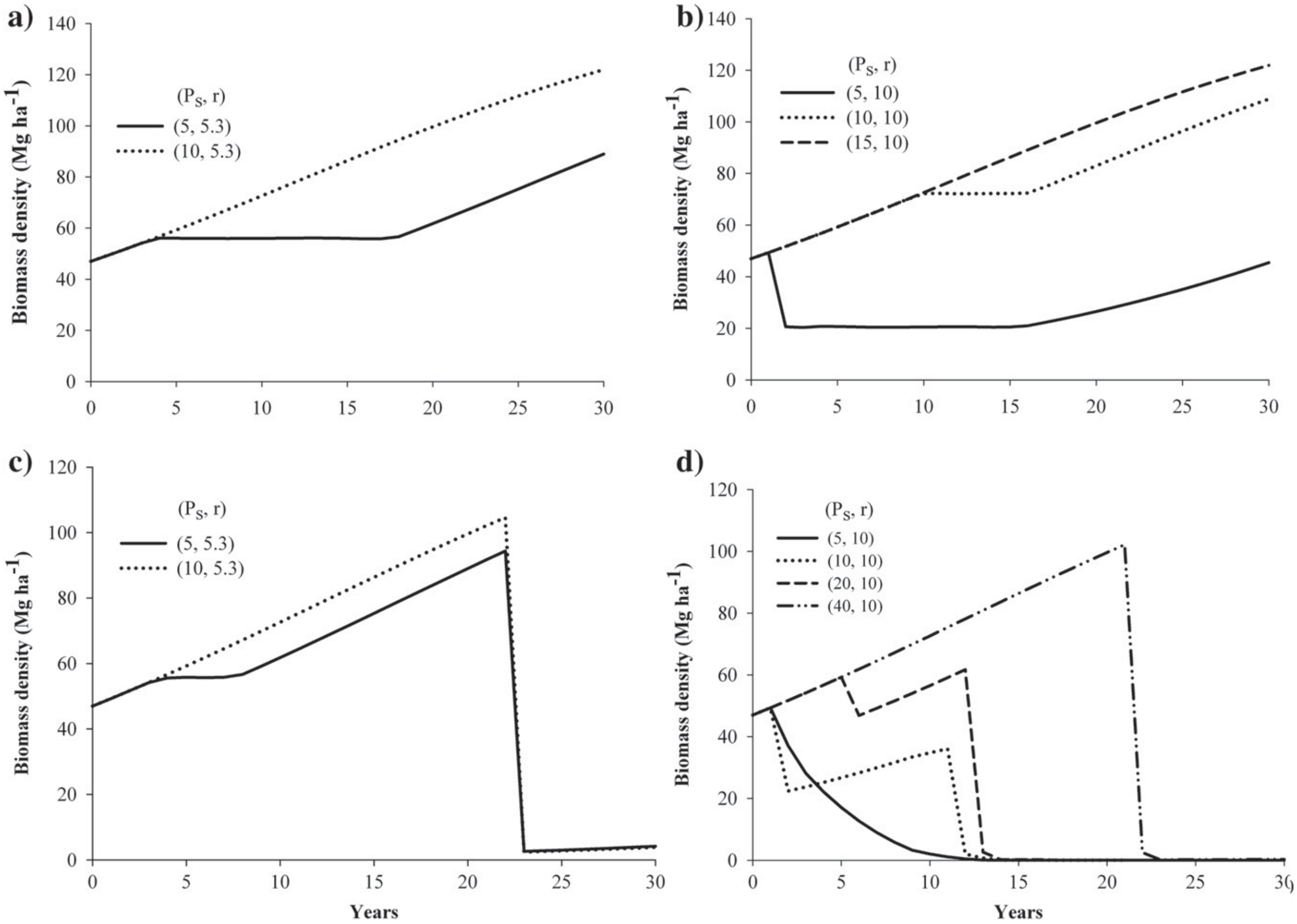

Fig. 6. Development of biomass stock, $S(t)$, over a 30 year period for 5.3% (right) and 10% (left) discount rates with different payments for carbon sequestration, P_s (5–40 USD $MgCO_2e^{-1}$), and baseline degradation equal to 4.3% of biomass stock annually. In the two upper panels biomass reduction beyond the baseline is taxed, while no such tax is levied in the lower panels.

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Paper IV

Past and present profitability of deforestation of miombo woodlands considering CO_2 emissions in Maseyu village Tanzania

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Abstract

The miombo woodlands of Tanzania have been subjected to continuous deforestation due to mainly agricultural expansion. Understanding the linkage between deforestation and economic efficiency of the subsequent land use is important for better land use planning and management. *Ex-post* cost-benefit analysis (CBA) was used to examine the profitability of conversion of unmanaged miombo woodlands into cropland considering the environmental cost of the activity in terms of emissions of CO_2. *Ex-ante* CBA was also used to compare profitability of keeping currently managed miombo woodland for the purpose of carbon sequestration with profitability of converting it into crop land. Net benefit (NB) of deforestation was calculated as the sum of agricultural rent and forest revenue during land conversion, minus cost of deforestation in terms of CO_2 emissions. NB of maintaining the managed woodland was based on returns from carbon sequestration. The NBs were discounted to provide an estimate of the net present value (NPV) of clearing and cropping, and maintaining the managed woodland. The value of CO_2 emissions and carbon sequestration was estimated by assuming different prices of CO_2 (USD ton^{-1}). Data collected from 54 randomly selected households were used for estimation of current maize and charcoal production in the area. Data required for the estimation of profitability of historic deforestation and carbon densities of the current land uses in the area were gathered from various secondary sources. Deforestation history was obtained from land use and cover change since 1964 reported from the area. A simple growth model was also developed to describe the biomass development of the woodlands and thus to estimate the carbon sequestration rate. We found that deforestation of miombo woodlands in Maseyu village has been, and still is, profitable if environmental costs of deforestation are not accounted for. However, fairly low prices of CO_2 emissions would make deforestation unprofitable in the social analysis. At 10 % discount rate, the break-even price was USD 11 tCO_2e^{-1} for the historic deforestation that took place since 1964 in the common land. At the same discount rate, CO_2 prices higher than USD 6 tCO_2e^{-1}would turn future deforestation of the managed woodland in Kitulangalo Forest reserve (KFR) unprofitable. Incorporating other environmental costs of deforestation such as loss of biodiversity and emissions of other GHGs could potentially reduce the profitability of deforestation further, particularly deforestation of the woodlands in the forest reserve.

Keywords: Deforestation; Maize production; Charcoal production; CO_2 emissions; Carbon sequestration; CBA; Profitability

1 Introduction

Smallholder farmers in Sub-Saharan Africa clear woodland and forest for agriculture because it is profitable to them (Namaalwa et al. 2001). In spite of low crop prices, such deforestation is profitable because better paid employment opportunities are scarce. The opportunity cost of labor in the African countryside is very low. Deforestation has a number of environmental consequences that affect the welfare of many people negatively, most prominently loss of biodiversity and emissions of greenhouse gases (GHG), particularly CO_2. The effects are of marginal interest to the farmers, however. Thus, deforestation that is profitable to individual agents has negative externalities that should be counted in the social analysis. GHG emission has a homogenous effect on climate (Vatn 2005), and has been traded (Linacre et al. 2011). Therefore, valuing the externality is possible. Valuing loss of biodiversity is more difficult since it depends on the specific biological loss and the effects it may have on various groups of people. Biodiversity protection has also been traded to a lesser extent (Walker et al. 2009). We analyzed social profitability of deforestation of miombo woodlands in Tanzania considering CO_2 emissions but not biodiversity loss. Understanding the linkage between deforestation and economic efficiency of the subsequent land use is important for better land use planning and management.

Miombo woodland, a collective name for woodlands dominated by species of the genera *Brachystegia*, *Julbernardia*, and *Isoberlinia*, is a common vegetation type in large parts of sub-Saharan Africa (Campbell 1996). The miombo region covers an estimated 2.4 million km^2 and supports the livelihoods of about 100 million rural and urban dwellers (Dewees et al. 2010). These woodlands cover about 36% of the total land area and about 90% of the forest and woodland ecosystems of Tanzania (Malimbwi et al. 2005). They have been declining at an average rate of about 1.06 % per year since the 1990s (FAO 2010), mainly due to agricultural expansion.

As an example of deforestation and agricultural expansion, we studied land-use of unmanaged woodland in the public land and managed woodland in Kitulangalo Forest Reserve (KFR) in Maseyu village in Morogoro region, eastern Tanzania. We undertook two investigations of social profitability of deforestation in this area – one *ex-post* cost-benefit analysis (CBA) of the deforestation that has actually taken place in the common land outside the forest reserve since 1964, and one *ex-ante* CBA of possible future deforestation within the reserve. The latter is motivated by the idea that some forest reserves might be degazetted in case crop production is highly profitable even when environmental costs of deforestation, in our case CO_2 emissions, are included in the analysis.

2 Materials and Methods

2.1 Study site

The study site, Maseyu village is located about 50 km east of Morogoro town along the Dar es Salaam-Morogoro highway (Figure 1). The village covers approximately 36,000 ha with about 2000 inhabitants. It comprises settlements (170 ha), croplands (215 ha), open miombo woodlands (woodland with scattered cultivation) (7000 ha), village reserve (150 ha), a part of (about 70%) the KFR (1700 ha) and a part of the Wami-Mbiki wild animals management area (WMA) (27000 ha). The woodlands on public land are openly accessible to the surrounding community. WMA is a community-based conservation area that was established in 1999. The WMA covers an area of approximately 4,200 km^2 and is surrounded by 24 villages including Maseyu (Madulu 2005). The woodlands inside the WMA have been subjected to extensive tree cutting for charcoal production and agricultural expansion. The KFR was gazetted in 1955 (GN198 of 3/6/1955) (Malimbwi and Mugasha 2001) and covers an area of about 2,452 ha, including the semievergreen forests in the Kitulangalo hills (Luoga et al. 2004). The central government and the village manage the part of the reserve located in Maseyu jointly. The current management system has been practiced since 2000. Cultivation and wood harvesting is prohibited within the reserve, but limited crop production, charcoal production and timber harvesting takes place illegally. The climate of the area is sub-humid tropical, with mean annual rainfall of 900 mm. The mean annual temperature is 24°C (Luoga et al. 2000). The vegetation is generally characterized as open dry miombo woodland, with some semi-evergreen forest (Luoga et al. 2000). The dominant tree species of the woodland are mainly used for charcoal making. As in other parts of the country, agriculture is the major occupation of the inhabitants. About 80 % of the households depend on small-scale crop production, about 10% depend on charcoal production and 5% depend on livestock keeping. The rest are engaged in other activities such as petty business and casual employment (Nduwamungu et al. 2008). Maize (*Zea mays* L.) is the most important crop in the village, accounting for about 85% of all the crops cultivated.

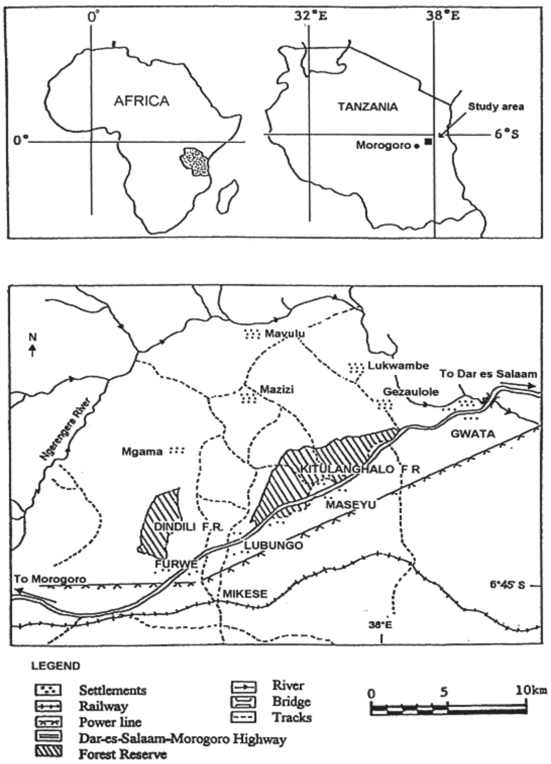

Figure 1. Location of the study site, source: Luoga et al. (2000)

2.2 Data

Data on costs and revenues related to crop and charcoal production were collected from 54 randomly selected households using structured questionnaires. Additional information on prices of inputs, crop produce and charcoal were obtained from the local markets. Data on statistics of current (nominal) local (farm-gate) and global (USA) price of maize, local price of charcoal, exchange rates and consumer price index (CPI) were gathered from secondary sources and are shown in Figures 2 and 3. Data on carbon densities in different pools of both the protected and unprotected woodlands, and the surrounding cultivated lands were also obtained from different published sources. Deforestation history was obtained from land use and cover change since 1964 reported from the area (Luoga et al. 2005).

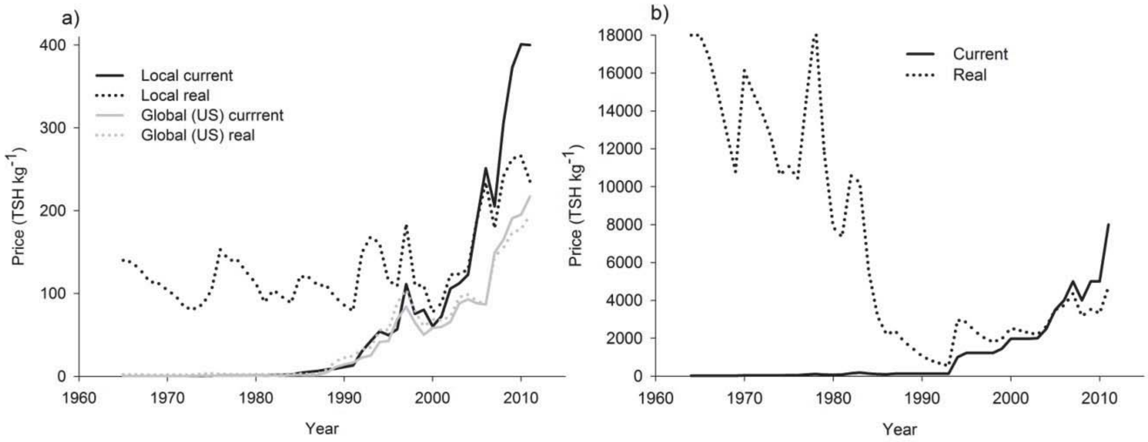

Figure 2. Current and real farm gate prices of maize in Tanzania and the USA from 1964 to 2011 (a), source: (Barreiro-Hurle 2012; Minot 2010; Morrissey & Leyaro 2007; Tapio-Biström 2001; USDA 2013) and current and real charcoal prices at the local market in Tanzania from 1964 to 2011 (b), source: (Hofstad & Sankhayan 1999; Malimbwi & Zahabu 2008)

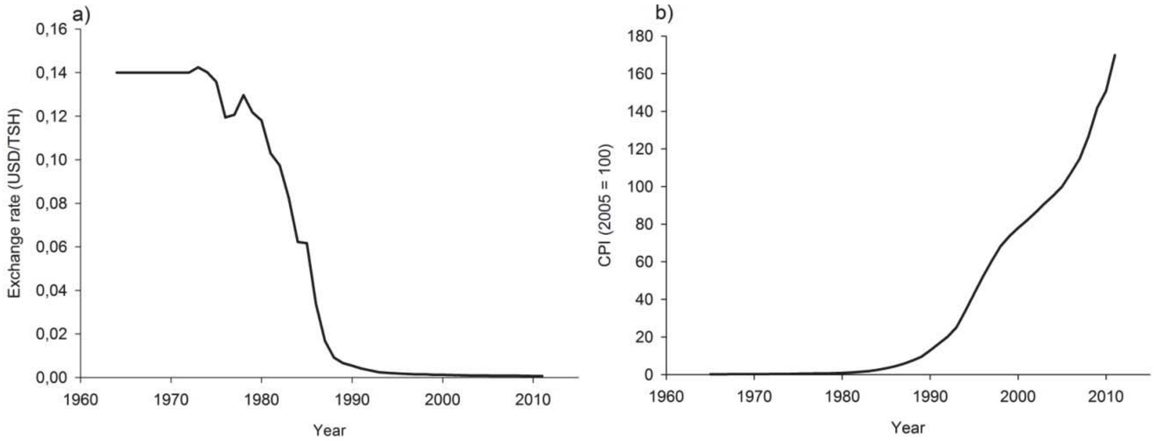

Figure 3. Tanzanian official exchange rates from 1964-2011 (a), source: (Index- Mundi 2011) and consumer price index (CPI) from 1964 to 2011 (b), source: (Index- Mundi 2011)

2.3 Land use and cover change

The process of land-use change involves the expansion of cropland, extraction of wood mainly for charcoal making, and in some cases grazing of cattle. The woodlands on public land have been reduced from 13,558 ha in 1964 to 10,755 ha in 1982 and to 6,782 ha in 1996 (Luoga et al. 2005). From these figures, annual deforestation rates were estimated and the woodlands have been declining at a rate of 1.3% of the total area from 1964 to 1982 and at a rate of 3.24% of the total area from 1982 to 1996. The deforestation rate after 1996 in the public lands as well as the potential deforestation rate in the forest reserve was estimated as an average of the two rates (2.14%).

2.4 Estimating carbon storage and sequestration

Data on aboveground biomass carbon and soil carbon of the woodlands were gathered from various sources (Munishi et al. 2010; Ryan et al. 2011; Shirima et al. 2011; Zahabu 2008). The belowground biomass (carbon) was estimated as 20 % of the aboveground biomass. The soil carbon of croplands on deforested miombo woodlands was estimated as 60 % of soil carbon in miombo woodlands (Walker & Desanker 2004). The carbon estimate was multiplied by the conversion factor of 3.67 to obtain carbon dioxide equivalents (eCO_2). The net CO_2 that will be emitted due to deforestation was calculated as the difference between the mean of the total carbon density of the woodlands and the carbon density under the cultivated land. Accordingly, the amount of carbon released into the atmosphere because of land conversion ranges from 35 t ha^{-1} (128 $teCO_2$ ha^{-1}) from the woodland on public land to 55 t ha^{-1} (202 $teCO_2$ ha^{-1}) from the woodland in the forest reserve. In the periods from 1964 to 1982, the amount of carbon stock of the woodlands on public land is assumed to be the same as the carbon stock of the woodlands in the forest reserve.

The amount of carbon sequestered by the woodland depends on the growth rate of the vegetation. Therefore, we developed a simple growth model, Verhulst (1838) equation (Figure 4a.) to describe the development of biomass of the woodland. The equation relates the stock, S, and the increment, $\dot{S}$, of biomass in the woodland: $\dot{S} = a\ S - b\ S^2$, where a and b are positive constants. The necessary data used to estimate the equation were obtained by Ek (1994) from permanent sample plots in the KFR. The constants a and b were estimated by fitting a linear regression model. Observations and the developed growth function are shown in Figure 4a. We used fitted versus residual plot (a constant variance test) to evaluate the model and it showed no bias and a constant variance with p-value of 0.469. Starting with the current average biomass density of the forest reserve, 40 t ha^{-1} (Zahabu 2008), and assuming no harvest or fire, the biomass density is predicted to grow for about 80 years until it reaches its maximum. However, Luoga et al. (2002) reported an annual wood removal of 1.12 ± 0.68 m^3ha^{-1} from the reserve. Using a 0.85 conversion factor from volume (m^3) of fresh wood to biomass (ton) (Malimbwi et al. 1994), this corresponds to 0.95 ± 0.578 $tha^{-1}yr^{-1}$. Under normal circumstances, fires occur in miombo woodlands every dry season. Since observations on plots affected by fire were excluded from our material, fire was considered afterwards. Barbosa et al. (1999) found that the average probability that a plot in wetter Zambezian woodland miombo burns in a particular year is approximately 37 %. Ryan and Williams (2011) reported that 5-6 % of live trees (dbh>5cm) were killed in fires in miombo woodland. By multiplying 0.37 by 0.05, we found that predicted biomass should be reduced by 1.85% when fire is considered. In the final analysis of biomass development in KFR we considered biomass reduction due to both fire and the illegal harvest. We assumed the illegal harvest as well as fire to be constant in all future (Figure 4b.).

2.5 Estimating benefits and costs of deforestation, crop cultivation and woodland preservation for carbon sequestration

The benefit items of deforestation (clearing and cropping) are crop produce and wood obtained during land conversion. Deforestation also involves cost of land clearing and environmental costs such as loss of biodiversity and emissions of GHGs. The type of environmental cost of deforestation considered in this study is only CO_2 emissions. The deforested land is assumed to be used for the production of maize, the major crop type cultivated in the village. Since application of commercial fertilizers is very limited in the study area, the only input cost considered in relation to maize production is the cost of seed. Most of the sample households depend on family members for labor and opportunity cost of labor in the area is nearly zero. Hence, the cost of labor required for different activities during the production process is not considered in the analysis. The median yield of maize estimated from the household survey data was 620 kg ha^{-1} and the average farm-gate price of maize in 2011 was 400 TSH kg^{-1}. Farm-gate price of maize in the USA were considered as an approximation of global price of maize.

Wood obtained during clearing is assumed to be used for charcoal production. The current average standing volumes of the woodlands on public land and the woodlands in the KFR are 14 m^3 ha^{-1}

and 65 m^3 ha^{-1}, respectively (Zahabu 2008). Tree species used for charcoal making represent 40 % of the standing volume and one m^3 of wood yields 4.3 bags of charcoal (56 kg bag^{-1}). The labor required to produce one bag of charcoal is 2.3 person-days (Hofstad 1997). The average price of a bag of charcoal in 2011 was 8000 TSH at the kiln site and 10000 TSH at the roadside.

The only benefit item of maintaining the protected woodlands is considered to be carbon sequestration. Currently, there is no cost involved related to maintaining or patrolling the forest reserve. Illegal harvest and fire are expected to continue (Figure 4b). Hence, there is no cost of management included in this study. Value of a ton of CO_2e emissions and carbon sequestration was estimated by assuming different prices of CO_2 (USD/ton).

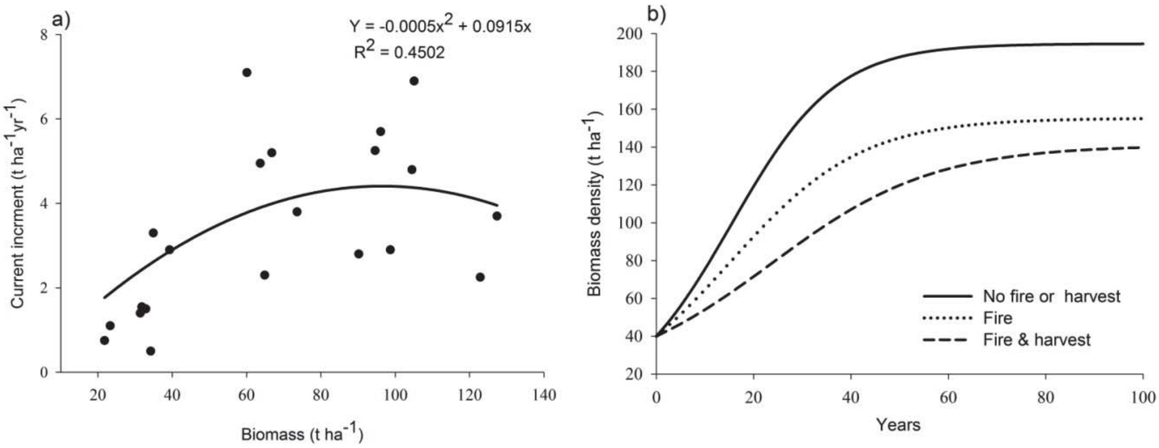

Figure 4. Observations of current increment and biomass density in KFR, with an estimated Verhulst growth function (a), and development of biomass density in KFR without fire or harvest, with fire alone, and with both fire and constant harvest of 0.95 t $ha^{-1}yr^{-1}$ (b).

2.6 Cost-Benefit Analysis (CBA)

In order to analyze the profitability of the deforestation that has actually taken place in the common land outside the forest reserve and possible future deforestation within the reserve, an *ex-post* and *ex-ante* CBA were undertaken, respectively. We estimated the financial returns to deforestation as the sum of agricultural rent and forest revenue during land conversion minus the environmental cost in terms of CO_2 emission. Net present value (NPV) of deforestation was used as a profitability criterion (Johansson & Löfgren 1985). The cost-benefit flows were discounted to provide an estimate of the NPV of clearing and cropping, and maintaining the managed woodland, respectively. The discount rate used in this estimation is a real interest rate, estimated by adjusting the nominal discount rate (12 %) for inflation (6.4 %). The nominal discount rate is based on the rate of lending by the Bank of Tanzania as of January 2011 and the inflation rate is the inflation rate of all items for the period January 2010 to January 2011 (BOT 2011). Accordingly, we used a discount rate of 5.3%, but further investigated the effect of increasing this rate to 10% and reducing it to 2.5% through a sensitivity analysis. Other parameter considered in the sensitivity analysis was cost of labor. The opportunity cost of labor might change in the future and hence an increase in wage rate was examined in the analysis of potential deforestation. If real discount rates are to be used the prices of all inputs and outputs should also be in real terms. Hence, the real prices of maize as well as charcoal were calculated using the current (nominal prices) (Figure 2) and CPI (base year 2005) (Figure 3b). All values are equivalent to 2005's value.

The global (USA) prices of maize were transformed to TSH by use of the 2005 exchange rate (Figure 3a).

3 Results and Discussion

Figure 5 shows that clearing the woodland on public land has been profitable when a ton of CO_2 was valued at less than TSH 14,600 and 9,800 when local and global real prices of maize were considered, respectively. The values are equivalent to USD 13 and 9 respectively (Table 1), using an exchange rate as of 2005. The results of sensitivity analysis showed that increasing the discount rate from 5.3 % to 10 % reduced the break-even price of a ton of CO_2 to TSH 12,500 (USD 11) and TSH 9,100 (USD 8), respectively. Deforestation was less profitable using the US price of maize as compared to Tanzanian price because the price in Tanzania was kept higher than world market prices early in the considered period. The high discount rate used in this study is within the range of the discount rates (8-15%) applied for agricultural projects in developing countries (Bond et al. 2010). Besides, given the level of poverty persisting in the miombo areas, a discount rate of 10 % per annum may be a reasonable assumption. Given the degraded state of woodlands in the common land in 1964, the shift from woodland to cropland could have been profitable even when we consider the social cost of CO_2 emissions. The conclusion depends on which price of CO_2 is considered realistic. The present low price in the EU market may be a result of the high volume of emission quotas distributed when the market was established (McGrath 2013; Zhang & Wei 2010). The reduction of biodiversity and other important ecosystem services following deforestation was not included in our analysis, however. This negative externality could have reduced profitability of deforestation significantly. On the study of the economics of deforestation in Ecuador, Wunder (2000) reported that the underlying cause of deforestation is that the natural forest provides less income than alternative land uses. He also suggested that considerable success in reducing deforestation can only be achieved when payments for global forest benefits are applied.

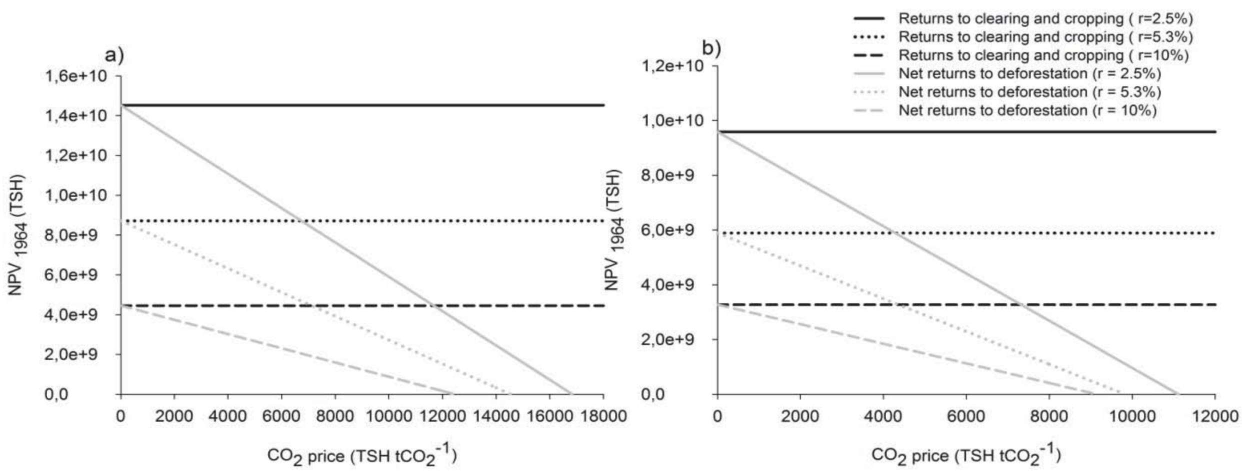

Figure 5. Social profitability of deforestation estimated using local price of maize (a) and global (USA) price of maize (b).

Table 1. Break-even prices of CO_2 emission (USD tCO_2e^{-1}) for the historic deforestation of woodlands in the common land.

Price of maize	Discount rate (real)		
	2.5%	5.3 %	10 %
Local price	15	13	11
US price	10	9	8

Table 2 shows that maintaining the protected woodland can be more profitable than the potential benefits of deforestation at a price of CO_2 higher than USD 9.5. Increasing the discount rate from 5.3 % to 10 % made managing the reserve profitable at a price of CO_2 higher than USD 6. Reducing the discount rate from 5.3 % to 2.5 % on the other hand increased the price of CO_2 where managing the woodland becomes profitable into higher than 18 USD ton^{-1}. When wage rate was increased from zero to the minimum wage rate of 2,692 TSH $manday^{-1}$, keeping the forest reserve for carbon sequestration became profitable at a price of CO_2 higher than USD 11.5, 6 and 3.5 for interest rates of 2.5%, 5.3% and 10%, respectively (Table 2). This implies that better employment opportunities in the area would make deforestation of the woodland in the reserve less profitable.

The miombo ecology is still relatively well protected inside the reserve. Future deforestation of the protected forest reserve does not seem to be a profitable land-use alternative from the perspective of the global community. Emission of CO_2 and lost opportunities to sequester additional quantities of CO_2 from the atmosphere make this management option non-profitable at fairly low values per ton of CO_2 emission. However, from the perspective of the local community, conversion of the reserve into cropland is a profitable activity. The similar conclusion in the *ex-ante* analysis of the reserve and the *ex-post* analysis of the common land is explained mainly by the fact that biomass density increment in the reserve is very low if the illegal wood harvesting and fire remain.

It is not possible to generalize the results from Maseyu to all of Tanzania, much less so to the whole of Sub-Saharan Africa. However, our results support the intuitive general insight that forests with low biomass density may be allocated to crop production while forests with higher biomass density and a potential for further biomass accumulation should be protected (Kaimowitz et al. 1998). This conclusion presupposes a certain productivity of land in crop production. One should keep in mind that this study did not investigate whether restoration of degraded woodland or establishment of forest plantations on such land are profitable means of climate change mitigation.

Table 2. Break-even price of CO_2 emission (USD tCO_2e^{-1}) for protection of KFR.

Wage rate	Discount rate (real)		
	2.5 %	5.3 %	10 %
Zero	18	9.5	6
Minimum wage	11.5	6	3.5

Conclusion

Deforestation of miombo woodlands in Maseyu village has been, and still is, profitable if environmental costs of deforestation are not accounted for. However, fairly low prices of CO_2 emissions would make deforestation unprofitable in the social analysis. At 10 % discount rate, depending on the prices of maize considered, this price ranged from USD 8-11 $tCO_2e^{-1}$for the historic deforestation that took place from 1964 in the common land. At the same discount rate, CO_2 prices higher than 3.5 - 6 USD tCO_2e^{-1}, depending on the wage rates applied, would turn future deforestation of the woodland in KFR unprofitable. The difference between the break-even price estimated using the *ex-post* analysis and *ex-ante* analysis is due to the fact that biomass density is higher inside the reserve than it was in the common land, and biomass density is likely to increase in spite of fire and illegal harvesting if the reserve is maintained. Lower discount rates would obviously lead to higher break-even prices of emissions. However, given the fact that the inhabitants in miombo areas prefer immediate consumption because of poverty, applying higher discount rate might be a reasonable assumption. Incorporating other environmental costs of deforestation such as loss of biodiversity and emissions of other GHGs could potentially reduce the profitability of deforestation further, particularly deforestation of the woodlands in the forest reserve.

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