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# Soil Organic Carbon in the Soil Scapes of Southeastern Tanzania

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door

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# Samenvatting

Bodemorganische koolstof vervult verschillende belangrijke functies. Als hoofdbestanddeel van de bodemorganische stof is het een belangrijke determinant van fysische, chemische en biologische bodemkenmerken en een maat voor de bodemproductiviteit. Dit is ven groot van belang in semi-aried en sub-humied Africa waar bodemdegradatie en verwoestijning mee aan de oorzaak liggen van voedselcrisissen en algemene verarming. Anderzijds is de opslag van koolstof in de bodem van groot belang in de strijd tegen verhoogde atmosferische koolstofconcentraties en klimaatsverandering. Ongeveer 1500 Pg organische koolstof zit wereldwijd opgeslagen in de bodem, drie keer zoveel als de koolstof in de vegetatie en twee keer zoveel als in de atmosfeer. Gezien tropische bodems 26% van de globale bodemorganische koolstofstocks omvatten kunnen ze een rol spelen als opslagreservoir.
Regionale schattingen van de bodemorganische koolstof zijn hoogst noodzakelijk gezien de onvolledige kennis van bodemkenmerken op globaal niveau, de hoge ruimtelijke variabiliteit en de vele factoren die invloed hebben op de opslag van koolstof. Dergelijke regionale studies worden gebaseerd op gegevens betreffende de bodem en het landgebruik. Waar het bodemtype bepalend is voor de hoeveelheid koolstofopslag op lange termijn, zullen vegetatiekenmerken de koolstofvariatie op korte termijn beïnvloeden.

Zuidoost Tanzania dient als typisch voorbeeld van bodemdegradatie en het verlies van bodemorganische koolstof ten gevolge van landgebruikveranderingen, ontbossing en een verhoogde landdruk. Lokale instellingen zijn gemotiveerd om deze problemen aan te pakken en tonen interesse voor het toepassen van bodembeschermende maatregelen, zoals het herbebossen van gedegradeerde bodems. Zulke maatregelen kunnen gesubsidieerd worden door het Clean Development Mechanism van het Kyoto Protocol, maar slechts indien de impact van deze maatregelen op de koolstofstocks correct meetbaar en verifieerbaar is. Dit maakt dat middelen voor het betrouwbaar opmeten en opvolgen van koolstofstocks, in relatie tot bodem, klimaat, landgebruik en landbeheer, van groot belang zijn in ontwikkelingslanden. Dit onderzoek zal in de eerste plaats focussen op de meting van koolstofstocks in het 415 ha grote studiegebied in zuidoost Tanzania, gebaseerd op bodemtype en landgebruik. Vervolgens zullen meettechnieken voor de bepaling van bodemorganische koolstof worden geoptimaliseerd met de nadruk op betrouwbaarheid en kostefficiëntie. Hierbij wordt vooral gekeken naar de ruimtelijke variatie van bodemorganische koolstof in het landschap.

De kartering van bodemorganische koolstof gebeurt op basis van een bodem en een landgebruikkaart. Een bodemkaart werd gecreëerd op basis van 280 volledige profielbeschrijvingen uit de beschikbare literatuur, aangevuld met 354 nieuwe profielbeschrijvingen die werden genomen door de auteur. Ruimtelijke aflijning van de bodemgroepen gebeurde op basis van een geologische en een topografische GIS-laag. De geologie bestaat uit sedimenten uit de Archaean periode waarop ten gevolge van fluctuaties van het zeeniveau een reeks jongere deposities werd afgezet. Van het oosten naar het westen is het gebied verdeeld in een kustgebied, plateaucomplex afgewisseld met riviervalleien, een regio van grote vlaktes en een westelijk gebied met plateaus en hooglanden. De oudste bodems, gelegen in de centrale vlaktes, zijn diep en homogeen en hebben een kleiige onderlaag. Het meest opvallend zijn de diepe rode Eutric Nitisols op de laagstgelegen gronden. Het grootste deel van de vlakte bestaat echter uit Arenic of Ferralic Phaeozems die werden gevormd in grof-getextureerde gneis. Op hellingen vond kleiuitspoeling plaats en werden Lixisols gevormd of, indien een vruchtbare toplaag aanwezig was, Luvic Phaeozems. Alle bodems gevormd op de sterk verweerde zandsteen ondergrond van de Krijtafzetting zijn diep en zandig: Arenic Ferralsols, Arenosols en (Ferralic) Arenic Phaeozems zijn de meest voorkomende bodems op de hoge plateaus terwijl Arenic Alisols en Acrisols werden teruggevonden op de hellingen. Op de grijze klei, mergel en kalksteen afgezet door de zee in het Boven-Krijt en Paleogeen werden vooral Gleysols en Vertisols gevormd. Een complex patroon van zandige bodems vormde zich op de afzettingen uit het Neogeen: Luvic Arenosols, Alisols en Ferralsols. Quaternaire afzettingen zijn aanwezig langs rivieren en langs de kustlijn. Deze bodems variëren sterk: langs de rivieren (Calcaric) Vertisols, Gleysols, Fluvisols en Phaeozems en langs de kust Arenosols.

Naast een bodemkaart is een landgebruikkaart nodig voor de opschaling van bodemorganische koolstof in de regio. Satellietbeelden van 1997 en 2005 werden gebruikt voor het karteren van het landgebruik. De

originele vegetatie van zuidoost Tanzania zou volgens verschillende auteurs bestaan uit gesloten droge kustbossen in de kustgebieden, op de plateaus en in de zuidelijke vlaktes, open bossen in de centrale en noordelijke vlaktes en mangrovebossen langs de kustlijn en in beschutte baaien. Ondanks de hoge ecologische waarde heeft het gesloten kustbos het meest geleden onder menselijke beïnvloeding: ten gevolge van een hoge populatiedruk in dit gebied blijft slechts 0.4% van de oorspronkelijke bedekking blijft over. In 1997 blijft nog een groot stuk kustbos bewaard op het minder bevolkte Rondo plateau, terwijl het grotendeels werd vervangen door secundaire struiksavanne in het kustgebied, cashewplantages op het Makonde plateau en landbouwland aangevuld met cashewplantages in de zuidelijke vlaktes. In 2005 is het areaal aan cashewvelden nog verder toegenomen op het Makonde plateau, aangevuld door meer dan 20% landbouwland. De sterke expansie van cashewvelden is typisch voor zuidoost Tanzania, waar de grootste hoeveelheid cashew van het land wordt geproduceerd. De centrale vlaktes en noordelijke plateaus waren oorspronkelijk bedekt met open bos, omdat de extreme seizoenale fluctuaties in bodemvocht de groei van gesloten bos onmogelijk maakten. Hoewel de totale oppervlakte aan open bos hier niet sterk is afgenomen, zijn grote delen verstoord en omgevormd tot secundaire vegetatie. In de grote vlaktes zijn boomgewassen vooral aangeplant op de vruchtbare Nitisols.

Wanneer de totale koolstofgehaltes worden berekend van de 210 bodemprofielen uit de literatuur en de 354 nieuw gemeten profielen kunnen koolstofstocks worden toegekend aan de beschreven bodems en landgebruiken. Bodemorganische koolstof wordt in het laboratorium gemeten als de massa C per bodemmassa (%C), maar voor opschaling naar landeenheden wordt het meestal uitgedrukt als een densiteit (Mg C.ha$^{-1}$ tot een bepaalde diepte). Deze wordt berekend door het %C te vermenigvuldigen met de bulkdensiteit. Niet al deze variabelen zijn gemeten in elke dataset, maar enkele belangrijke kunnen wel worden afgeleid op basis van andere bodemkenmerken.
Koolstofpercentages kunnen gemeten worden op basis van verschillen technieken, bijvoorbeeld natte of droge oxidatie of spectroscopie. Een snelle en goedkope manier om bodemorganische stof te meten is gloeiverlies. Hierbij wordt organische stof verwijderd uit een ovendroog bodemstaal (gedroogd op 105°C) door verbranding (op 375 tot 600°C) in een moffeloven. Regressievergelijkingen kunnen gebruikt worden om bodemorganische koolstof af te leiden uit bodemorganische stof. Het wordt sterk aangeraden om lokale regressievergelijkingen op te stellen gebaseerd op een intercept model. Hier werden uit een subset van 100 stalen, geselecteerd uit de meest voorkomende bodems en landgebruiken, 2 regressievergelijkingen opgesteld, voor de A en de B- horizonten. De grootte van het intercept en de lage waarde van de hellingsparameter in de vergelijking van de B-horizont zijn het gevolg van gewichtsverlies door andere anorganische bodemcomponenten. In de bodems van het studiegebied wordt dit gewichtsverlies vooral bepaald door de desorptie van kleiwater van kaoliniet, het verdwijnen van hygroscopisch water van vermiculiet en illiet, dehydratie van gibbsiet en goethiet en het verlies van water uit de kristalroosters van gibbsiet en goethiet. Met behulp van deze formules kan de bodemorganische koolstof worden berekend van alle bodemstalen waarvan de bodemorganische stof is bepaald met gloeiverlies.
De bulkdensiteit van een bodem is de massa van een ovendroog ongestoord bodemstaal per eenheid volume. De bulkdensiteit is een belangrijk fysisch bodemkenmerk en is noodzakelijk om bodemkenmerken per eenheid massa om te zetten naar eenheid volume. Daarom is het een onmisbare variabele voor de meting van koolstofstocks in de bodem. Omdat de methode tijdrovend en arbeidsintensief is wordt het echter vaak niet gemeten in routineonderzoek van bodemprofielen. Een schatting van de bulkdensiteit kan wel worden afgeleid van andere bodemkenmerken met behulp van een pedotransferfunctie. Algemeen wordt geadviseerd om regiospecifieke pedotransferfuncties te kalibreren en valideren. In deze studies werden 5 modellen getest op basis van 153 horizon beschrijvingen. Meervoudige regressie gebaseerd op 3 variabelen (organische koolstof, textuur en diepte) werd gekalibreerd en gevalideerd en de beste functie werd geselecteerd. Hieruit bleek dat de bulkdensiteit in deze studie in de eerste plaats af hangt van het kleigehalte en in de tweede plats van de diepte van het staal, maar niet van de hoeveelheid koolstof. Goed ontwikkelde microstructuren die ontstaan in kleiige bodems door de aggregatie van negatief geladen kleimineralen zoals kaoliniet met sesquioxides veroorzaken een lagere bulkdensiteit. Lagere bulkdensiteiten hoger in het profiel zijn waarschijnlijk het gevolg van een gecombineerd effect van hogere concentraties aan organische koolstof en meer decompactie door biotische activiteit van bodemfauna en wortels. Het feit dat de functie niet direct afhangt van het gehalte aan organische koolstof, in tegenstelling tot het merendeel van de functies gevonden in de literatuur, benadrukt het belang van het opstellen van lokale pedotransferfuncties. Indien textuur en staalnamediepte

beschikbaar zijn uit profielbeschrijvingen uit de literatuur, kunnen deze nu gebruikt worden om de bulkdensiteit te berekenen.
Het is algemeen bekend dat bodemorganische koolstof afneemt met de diepte. De verticale verdeling kan geschat worden door het fitten van vergelijkingen uit de literatuur. Hieruit werden drie significant verschillende logaritmische vergelijkingen afgeleid, afhankelijk van het vegetatietype.
In open bos en struiksavanne wordt een groot gedeelte van de bodemkoolstof opgeslagen in de bovenste bodemlagen. Dit is het gevolg van de slechtere afbreekbaarheid van de koolstofinputs ten opzichte van gras- en landbouwland. De diepere verdeling in landbouwland kan verder nog het gevolg zijn van bodemverstoring tijdens de aanleg van het veld, hoewel in het studiegebied algemeen weinig wordt geploegd. Cashewplantages hebben een intermediaire verticale koolstofverdeling vermits de vegetatiestructuur kenmerken vertoont van beide andere systemen: een boomlaag van cashew en een onderlaag van gras of gewassen. De voorgestelde formules kunnen nu gebruikt worden om bodemorganische koolstof te schatten op dieptes die niet gemeten zijn in bepaalde datasets.

Met de hiervoor beschreven methoden is het mogelijk geworden om bodemorganische koolstofstocks te berekenen voor de 210 profielbeschrijvingen uit de literatuur en de 354 nieuw gemeten profielen. Hiermee kan de relatie bepaald worden tussen de totale bodemorganische koolstof, het bodemtype en het landgebruik. Deze waardes worden vervolgens toegekend aan landschapseenheden, die gevormd worden door intersectie van een bodem- en een landgebruikkaart.
De gemiddelde koolstofstock tot 1m diepte is 73 $Mg.ha^{-1}$, wat vergelijkbaar is met andere studies uit Oost-Afrika. De bodems die het hoogste potentieel bieden om koolstof op te slaan zijn Vertisols, Phaeozems, Umbrisols en Nitisols (gemiddelde koolstofstocks van 106 $Mg.ha^{-1}$). Hoewel ze minder dan 40% van de totale oppervlakte omvatten, dragen ze bij tot bijna 60% van de totale koolstofstock in 2005. Langs de andere kant zijn het juist deze bodems die hebben bijgedragen tot 50% verlies aan bodemkoolstof ten gevolge van veranderingen in landgebruik tussen 1997 en 2005. Vooral de lemige Phaeozems en Umbrisols zijn hiervoor zeer gevoelig. Ze bevatten een hoge hoeveelheid koolstof bevatten in de A-horizont maar binden deze niet zo sterk in oreganominerale complexen als de meer kleiige bodems. Alisols, Acrisols, Lixisols, Ferralsols, Arenosols en Ferralic/Arenic Phaeozems hebben een significant lagere koolstofstock (gemiddeld 87 $Mg.ha^{-1}$). Koolstof onder Gleysols is intermediair (87 $Mg.ha^{-1}$), wat waarschijnlijk het gevolg is van de verhinderde groei van stuiken en bomen op deze bodems. Gesloten bos, open bos en struiksavanne van meer dan 20 jaar oud bevatten gemiddeld tussen 66 en 70 Mg $C.ha^{-1}$. De relatief lage koolstofstocks kunnen geweten worden aan het selectief overblijven van de natuurlijke vegetatie op de armste bodems, de open structuur van de vegetatie met geringe grondbedekking, de menselijke verstoring en het effect van regelmatige bosbranden. Als de open bossen echter behouden blijven op vruchtbare bodems kunnen ze wel veel koolstof opslaan, zoals de 120 $Mg.ha^{-1}$ waargenomen op Nitisols. Het traditionele rotationele landbouwsysteem, is in staat om hoge koolstofstocks in de bodem te behouden (120 $Mg.ha^{-1}$ in jong braakland en 98 $Mg.ha^{-1}$ in landbouwland zonder maniok).

Op de minder vruchtbare bodems of wanneer landbouw continu wordt verkiezen de boeren de aanplanting van maniok, omdat dit gewas resistent is tegen droogte en een lage bodemvruchtbaarheid. Koolstofstocks onder cassava zijn slechts half zo hoog (39 $Mg.ha^{-1}$) als onder de andere landbouwgewassen. Het inkorten van de braakperiode en de omvorming naar permanente landbouw zal sterke implicaties hebben voor de regionale koolstofstocks. Een andere bedreigen wordt gevormd door de uitbreiding van de cashewplantages, die in 2005 reeds 33% van het studiegebied bedekten. Deze velden hebben de tweede laagste stock (50 Mg $C.ha^{-1}$) wat kan worden verklaard door het verwijderen van gras, ondergroei en strooisel; een algemeen gangbare praktijk die de oogst van cashewnoten vergemakkelijkt. Indien andere gewassen tussen de jonge cashewbomen worden aangeplant, kan dit de gemiddelde koolstofstocks verhogen tot 79 $Mg.ha^{-1}$ , maar wanneer na 20 jaren de cashewbomen zo groot worden dat er slechts weinig plaats overblijft voor andere gewassen, verdwijnt dit positieve effect grotendeels. Graslanden, rijstvelden en groentetuintjes zijn minder vaak voorkomende landgebruiken, die vooral teruggevonden worden op de meest vruchtbare bodems en die de hoogste koolstofstocks hebben (tussen 114 en 128 $Mg.ha^{-1}$). De totale koolstofstock van het studiegebied werd geschat op 34.50 Tg in 1997. Na het berekenen van de veranderingen in landgebruik gedurende 8 jaar tijd werd geschat dat deze stock afnam met 14%. Hieruit kan geconcludeerd worden dat de intensificatie van het landbouwsysteem, het planten van cassava op verarmde bodems en de expansie van de cashew monocultuur een serieus verlies in bodemorganische koolstof hebben veroorzaakt. Mogelijke oplossingen zijn het herstellen van het

traditionele rotatiesysteem, het tussenplanten van cashew met andere gewassen op een substantieel gedeelte van veld en herbebossing.

Hoewel (her)bebossing kan leiden tot een verhoogde koolstofopslag, zijn betrouwbare metingen van bodemkoolstof moeilijk te verkrijgen gezien de hoge ruimtelijke variabiliteit. Een goede kennis van de koolstofstocks en hun ruimtelijke variabiliteit kan leiden tot een proefnameschema dat zowel betrouwbaarheid is als kostefficiënt. Bij staalname moet rekening gehouden worden met zowel het aantal stalen als de densiteit ervan in relatie tot de ruimtelijke schaal van de variatie. Voor zowel het karteren als het berekenen van het gemiddelde van bodemorganische koolstof in een proefvlak kunnen de ruimtelijke intervals geoptimaliseerd worden door het toepassen van klassieke statistische en geostatistische theorieën. De optimale afstand van staalname voor het berekenen van gemiddelde koolstofstocks varieert tussen 36m (in het fragmentarische open bos) en 422 m (in het gehomogeniseerde cashewplantage). Het aantal stalen varieert tussen 6 en 72 (1 Mg $ha^{-1}$ precisie) voor respectievelijk cashew plantage en gesloten bos. Een rechthoekig rooster met een interval van 25m kan gebruikt worden voor het karteren van koolstof met een puntkriging schattingsfout van 3.0 Mg $ha^{-1}$ in het gesloten bos, 2.6 Mg $ha^{-1}$ in het open bos, 2.2 Mg $ha^{-1}$ in de teakplantage en 1.1 Mg $ha^{-1}$ in de cashewplantage. Vermits het dennenbos geen ruimtelijke structuur heeft, kunnen stalen random genomen worden en bestaat de beste bodemkaart uit de gemiddelde koolstofwaarde die wordt toegekend aan het hele veld. Het is bewezen dat schema's voor het meten en karteren van bodemorganische stof sterk variëren ten gevolge van de verschillende ruimtelijke patronen in bossen en afhangen van de vereiste precisie en de vereisten van het onderzoek. Slechts wanneer de juiste strategie wordt kan een hoge betrouwbaarheid worden bereikt zonder economische verliezen of statistische misinterpretaties.

Naast ruimtelijke structuren in bodemorganische koolstof resulterend van vegetatiepatronen, kunnen andere factoren lokaal de ruimtelijke heterogeniteit bepalen. Een belangrijke factor in het Tanzaniaanse landschap is de aanwezigheid van termieten en hun heuvels. Termieten beïnvloeden de bodem op verschillende vlakken: ze hebben een invloed op de profielontwikkeling, op de fysische zowel als chemische bodemkenmerken, op de bodemmicrobiologie en op de plantengroei. Vandaar dat termietenconstructies en vooral heuvels beschouwd worden als 'eilanden' van heterogeniteit in het ecosysteem. Deze kleinschalige heterogeniteit wordt meer en meer beschouwd als vitaal voor het behoud van de biodiversiteit en voor het verspreiden van risico's in gewasproductie op het niveau van het veld. Er was tot noch toe geen informatie beschikbaar over de termietendiversiteit van zuidoost Tanzania en hun invloed op de typische bodems van de regio. Het doel van deze studie was het karakteriseren van de ruimtelijke patronen van bodemorganische koolstof in en rond termietenheuvels. Hiervoor werden drie locaties geselecteerd die de typische variatie in bodemtype, hoogte en landeenheid weergeven. Op elke plaats werden drie proefvelden van 1 ha gekozen met 3 veel voorkomende landgebruiken: natuurlijke bos, landbouwgewassen en cashewplantages. Hierop werd de termietendiversiteit werd bestudeerd gebaseerd op de transectmethode en werd de bodemorganische koolstof gemeten in en rond termietenheuvels. De termietendiversiteit nam af van natuurlijk bos over cashewplantages naar landbouwland ten gevolge van een dalende kroonbedekking en dus bodemvochtigheid. Bodemetende termieten worden het meest beïnvloed door de conversie van bos naar landbouw. Op landbouwvelden worden vooral pestsoorten aangetroffen. Gemiddeld 43 (kleine) Termitinae heuvels en 5 (grote) Macrotermitinae heuvels werden aangetroffen per ha. De hoeveelheid organische koolstof in de Macrotermitinae heuvels zijn ongeveer 1.5 keer hoger dan in de referentiebodem. Deze kleine toename is het gevolg van het gebruik van speeksel in het bouwen van de heuvels. Termitinae heuvels bevatten gemiddeld 3.5 keer meer organische koolstof dan de referentiebodem, vermits hier vooral feces worden ingewerkt. De totale hoeveelheid koolstof in een Macrotermitinae heuvel bedraagt gemiddeld 754.8 kg C (wat neerkomt op in totaal 3759 kg per hectare), terwijl slechts 0.5 kg koolstof wordt opgeslagen in een Termitinae heuvel (ofwel 21 kg per hectare). Dus hoewel Termitinae een grotere impact hebben op de percentages C in het bodemmateriaal, is totale effect op het veld klein door het kleine volume van de heuvels. Als niet alleen de heuvels worden meegeteld maar ook de bodem er rond, die eveneens is aangerijkt aan koolstof, kan berekend worden dat een veld beïnvloed door termieten gemiddeld 12 Mg $ha^{-1}$ meer koolstof bevat dan een referentiebodem, ofwel 6%. Een gestratificeerde staalname in en rond de termietenheuvels is absoluut noodzakelijk om de koolstofstocks van deze velden correct in te schatten, en om veranderingen ten gevolge van landgebruikveranderingen te kunnen onderscheiden.

# Summary

Soil organic carbon (SOC) is well known to maintain several functions. On the one hand, being the major component of soil organic matter (SOM), it is a determinant of soil physical and chemical properties, an important proxy for soil biological activity and a measure of soil productivity. Land use management that will enhance soil carbon (C) levels is therefore important for farmers and land use planners, particularly in semiarid and sub-humid Africa where severe soil degradation and desertification are related to perpetual food crises and overall impoverishment. On the other hand, C sequestration in the soil is an important climate change mitigation measure. The global SOC stock is about 1500 Pg, which is about three times the amount of organic C in the vegetation and twice the amount of C in the atmosphere. Since tropical soils store 26% of the SOC stocks of the world they could serve as C storage reservoirs. Due to an incomplete knowledge of specific soil properties at a global scale and, high spatial variability of SOC and the different effects of the factors controlling SOC, regional studies of SOC are necessary to refine global estimates. Both soil and land use data should be used in determining regional SOC. While soil factors are important, as are climatic factors, in explaining C storage or pools over long periods of time, changes in vegetation or land use determine the changes in C sequestration over shorter periods.

southeastern Tanzania serves as a typical example of soil degradation and SOC losses through land use change, deforestation and increased land pressure on the African continent. Therefore any policies geared to the significant reduction of current and future emissions as well as the sequestration of carbon from the atmosphere should target the forest and land-use sectors. Local institutions have shown their interest in tackling these problems and in implementing soil conservation management measures such as reforestation of degraded soils, which could be funded by the Clean Development Mechanism of the Kyoto Protocol. In this way C sequestration opportunities could go hand in hand with local conservation of natural resources as well as poverty alleviation. However, the Kyoto Protocol limits reporting of C sequestration activities to those that are both "measurable and verifiable". Even if allowed as part of an accounting system, credit for C sequestration activities could be withdrawn if high standards of measurement cannot be met. Tools for monitoring, verification or certification will be needed in developing countries in order to measure the changes in C pools in relation to soil type, climatic conditions, land occupation and different land management practices.

This research will therefore in the first place focus on SOC budgeting in the 415 ha large study area in southeastern Tanzania, based on soil and land use properties. Secondly, SOC measuring techniques that are both cost efficient and reliable will be developed based on the spatial variation of SOC in the study area.

Mapping and upscaling of SOC in southeastern Tanzania will be based on soil and land use maps. However, no reliable soil map was available that could be used as a base for this study. Therefore, a soil map was created, based on 280 full profile descriptions available from the literature, supplemented with 354 new profile descriptions that were made by the author in the scope of this work. Soils were classified according to the World Reference Base. Spatial delineation of the boundaries was based on a geology and a topography layer in a GIS-environment. The geology consists of old basement sediments of the Archean period. As a result of relative fluctuations of land and sea levels and recurrent marine transgression and regression, a series of younger deposits has been laid down parallel to the shore. From east to west, southeastern Tanzania can be divided into a coastal area, an area of plateaus and floodplains, a central area of plains and a western area of plateaus and uplands. The oldest soils of the region are those of the large plains situated on Basement rocks. All these soils are deep and homogeneous with clayey subsoil. The most remarkable examples are the deep red Eutric Nitisols in the low areas of the central plains. The largest part of the plains consists of Arenic or Ferralic Phaeozems which were formed on coarse-grained gneisses. Where clay illuviation resulted in an argic horizon, mainly on slopes around the higher plains, Lixisols were formed. On the inclined terrain with gneisses and quartzites of both the northern and the southern plains, erosion lead to a finer texture and clay illuviation effected in argic horizons. This resulted in Lixisols or, when fertile A-horizons were found, Luvic Phaeozems. All soils derived from the strongly weathered sandstone beds of Lower Cretaceous origin are deep and sandy: Arenic Ferralsols, Arenosols and (Ferralic) Arenic Phaeozems are the most common soils on the high plateaus while Arenic Alisols and

Acrisols were observed on the slopes. On marine deposits of grey clays and marls and limestones from the Upper Cretaceous and Paleogene mainly Gleysols and Vertisols are formed. A complex pattern of sandy soils was formed on the marine and terrestrial layers of the Neogene: Luvic Arenosols, Alisols and Ferralsols. Quaternary deposits are present along the main rivers and at the coastline. Soils are variable: along the rivers (Calcaric) Vertisols, Gleysols, Fluvisols and Phaeozems are seen. At the coastline Arenosols are present.

Besides a soil map, a land use map is necessary for SOC upscaling across the region. Land use maps from 1997 and 2005 were used to estimate land use changes that have occurred in the study area. Several authors stated that the original vegetation of southeastern Tanzania consists of forest or forest-woodlands. More specific, coastal forests are the natural vegetation type of the coastal area, plateaus and southern part of the plains, miombo woodlands are naturally occurring in the rest of the plains and mangrove forests are naturally growing at the coastline and in sheltered bays. Despite its high ecological value, the coastal forest has suffered most from human intervention: only 0.4% of the coastal forest remains. The reason is the greater population in these areas, which is a historical development. In 1997 the coastal forest remained mainly on the less populated Rondo plateau but was replaced by secondary bushland in the coastal area, cashew on the Makonde plateau and cropland with tree crops in the southern plains. Towards 2005 cashew expanded even more on the Makonde plateau, complemented by more than 20% of cropland. The large expanse of cashew groves is typical of southeastern Tanzania, where most of the nation's cashew is produced. The central plains and northern plateaus were formerly covered in woodland, since the extreme seasonal fluctuations in soil moisture were unsuitable for forest growth. Although the total area of woodland in the study area has not much declined, large parts of it have been disturbed and been converted to secondary vegetation. In the large plains, areas with tree crops have expanded mainly on the fertile Nitisols. The rest of the area still remains largely under woodland cover.

Attributing SOC stocks to the soils and land uses that were just described can be done after calculating the SOC of 210 profiles from the reference dataset and 354 profiles sampled by the author. SOC is measured in the laboratory as the mass of C per soil mass (%C), but for upscaling to land units it is expressed as a C density (Mg C.ha$^{-1}$ to a certain soil depth). This can be calculated by multiplying %C with the bulk density. However, not all these variables are given for every dataset. They can however be estimated based on other soil properties using following methods.

C percentages can be measured using different techniques, for example wet oxidation, dry oxidation or reflectance spectroscopy. A cheap and fast way of measuring soil organic matter is loss-on-ignition. It involves the removal of organic matter from an oven dry sample (dried at 105°C) by combustion of the sample at medium temperature (375 to 600°C) in a temperature-regulated muffle furnace. Regression equations can be used to derive SOC from SOM by loss-on-ignition. A regional regression equation was developed based on an intercept model for a subset of 100 samples, which were selected from most types of soil and land-use in the study area. This resulted in two different regression equations, one for the topsoil and one for the subsoil. The intercept and the low value of the slope parameter for the subsoil can be explained by weight loss of other, inorganic, soil constituents. In the soils of the study area, this additional weight loss could be attributed to the desorption of clay water from kaolinite, removal of hygroscopic water of vermiculite and illite, dehydration of gibbsite and goethite and dehydroxylation of gibbsite, goethite and hydroxyl-interlayered minerals. All these minerals are very common in the old soils found in the area. With these formulae all data tested for SOM with loss-on-ignition can now be converted to SOC.
The soil bulk density is the mass of an oven-dry sample of undisturbed soil per unit volume. Bulk density is an important physical property which is needed for mass to volume or area conversions of soil properties; therefore it is indispensable for the assessment of soil C stocks and nutrient pools and it is the mandatory measuring unit for soil C assessment and accounting. Unfortunately, bulk density is not always determined in routine soil surveys, as the procedures are tedious, labour-intensive, time-consuming and expensive. To overcome this problem, pedotransfer functions are frequently used, which translate basic soil data into another soil property, in this case bulk density. It has been advised to calibrate and validate specific pedotransfer functions on a regional basis to enhance the accuracy and precision of bulk density prediction. Five model types of pedotransfer functions described in literature were tested against 153 horizon descriptions. By performing multiple regressions on five models based on three variables (organic

carbon, texture and depth) and performing calibration and validation tests, the best function was selected. The best model for estimating bulk densities was a logarithmic function based on clay content and depth, but not on the organic carbon content. In clay-rich soils well-developed microstructures caused by the aggregation of negatively charged clay minerals such as kaolinite with sesquioxides could lower the bulk density more than the small effect of the low organic carbon content. Lower bulk densities higher in the profile are probably the result of the combined effect of higher organic matter contents and more decompaction by biotic activity of soil fauna and roots in the topsoil versus the subsoil. If texture and sampling depth are available from soil profile descriptions found in literature, they can now be used to derive the bulk density, which is often lacking from these data.
SOC is known to decrease with soil depth. The vertical SOC distribution can be estimated by fitting different equations found in literature. The result showed that the vertical distribution depends on the vegetation. In woodlands and bushlands a high proportion of SOC is stored in the upper layers and SOC distribution is shallow. The relatively low decomposability in wood- and bushland could increase SOC storage in surface soils compared to grasslands and croplands. The deeper distribution of C in croplands could also be the result of soil disturbance during clearing and preparation of the field, although soil preparation and ploughing is uncommon in the study area. Cashew fields have intermediate vertical SOC distributions. The vegetation structure shows elements of the two other systems with a tree layer of cashew trees and sometimes an undergrowth of grass or crops. The developed equations can be used to estimate SOC at depths which are not measured in certain datasets.

With the previously described methodologies it is now possible to calculate SOC stocks for the 210 profile description from the literature and the 354 profiles sampled by the author. Both soil type and land use determine SOC stocks. Soil texture influences C dynamics through the formation of organo-mineral complexes that protect C from microbial oxidation which is enhanced by the high surface area of the fine silt and clay fractions. The equilibrium soil C stock, which is the result of a balance between the rate of SOC inputs and rate of mineralization, is disturbed by land use change until a new equilibrium is eventually reached in the new ecosystem. Conversion of natural vegetation to various land uses results in very rapid declines in soil organic matter and a release of C to the atmosphere. Globally, the long-term flux of C from changes in land use (1850-2000) released 165 Pg C to the atmosphere, about 60% of it from the tropics and 8% from tropical Africa.
The study area of 415 Kha was divided into landscape units by intersecting the soil map and the land use maps of 1997 and 2005, thus generating landscape units. SOC stocks were attributed to these landscape units by assessing the relationship between SOC, soil type and land use. This information was used to create SOC maps of the study area and to calculate the total size of the soil carbon reservoir. The average SOC stock to 1m depth in the study area is 73 $Mg.ha^{-1}$, which is comparable to other studies in Eastern Africa. The soils that can store the highest amounts of SOC in the study area are Vertisols, Phaeozems, Umbrisols and Nitisols (average SOC stock of 106 $Mg.ha^{-1}$). Although they cover less than 40% of the total area, they contribute to almost 60% of the total SOC stock in 2005. However, they also contributed to 50% of the total SOC loss due to land use changes between 1997 and 2005. This can be mainly attributed to the loamy Phaeozems and Umbrisols, which have a high SOC content in their A-horizon but which offer no protection in organo-mineral complexes such as in clayey soils. Alisols, Acrisols, Lixisols, Ferralsols, Arenosols and Ferralic/Arenic Phaeozems have significantly lower SOC stocks (average of 87 $Mg.ha^{-1}$). SOC stocks of Gleysols are intermediate at 87 $Mg.ha^{-1}$, which is mainly the result of the impeded growth of bushlands on these soils.
Remnants of closed forest, woodlands and bushlands of more than 20 years have SOC stocks between 66 and 70 $Mg.ha^{-1}$. The relatively low SOC stocks can be attributed to the retaining of natural vegetation on the poorest soils, to the open structure of the vegetation with often little ground cover and to the disturbances by humans and fire. However, if woodlands are preserved on fertile soils they can have high SOC stocks, for example 120 $Mg.ha^{-1}$ on Nitisols.
The traditional cropping system, which consists of several years of cultivation followed by several years of bush fallow, is able to maintain high SOC stocks (120 $Mg.ha^{-1}$ in young fallow bushland 98 $Mg.ha^{-1}$ in cropped fields without cassava). On less fertile soils and when cropping becomes continuous, cassava becomes most important, since it is the most resistant to drought and low fertility. SOC stocks under cassava are less than half (39 $Mg.ha^{-1}$) of those under other crops. Shortening of the fallow period and conversion permanent agriculture will have serious implications on the SOC stocks. Another threat for the regional SOC stocks is the expansion of cashew plantations, which in 2005 already covered 33% of the

study area. Tree crops have the second lowest average SOC stock (50 $Mg.ha^{-1}$) which can be attributed to the removal of grass, undergrowth and litter by farmers to facilitate harvesting of cashew seeds. Planting other crops between the young trees (<20 yr) enhances the mean SOC stocks (to 79 $Mg.ha^{-1}$) but after 20 years this effect completely disappears, since crops can only be grown in the small spaces that remain between the old trees. Grasslands, rice fields and homestead gardens are less common land uses, which occur mostly on the fertile soils and which have among the highest SOC stocks (mean total values between 114 and 128 $Mg.ha^{-1}$). Total SOC stocks of the study area were estimated at 34.50 Tg in 1997. Based on the changes in land use during 8 years time it was estimated that this stock reduced with 14%. It can be concluded that intensification of the agricultural system by reducing the fallow period and planting of mainly cassava on the depleted soils as well as the large expansion of the cashew monocultures have caused a serious loss of SOC from the study area. Restoration of the traditional fallow system, intercropping of cashew trees with crops on a substantial area of the field, also after 20 years, and reforestation could be used to restore SOC stocks.

Although sequestration of SOC through aforestation or reforestation proved favourable, these measures are restricted by the ability to produce rapid, cost-effective and precise sampling schemes. Reliable measurements of SOC content are hard to get and labour-intensive due to the spatial variability. A good knowledge of the soil C stock and its spatial variation leads to a sampling strategy that is balanced between reliability and cost-effectiveness, in agreement with the error that is allowed for the purpose of the study. Factors to take into account are sample size and sample density in relation to the spatial scale of the variation. Sampling intervals can be optimized for soil mapping and for calculating average values by application of classical and geostatistical theories. In tropical forest soils geostatistic analyses were not yet used to develop sampling strategies. Therefore a SOC variability study was conducted in five common forest/woodland/plantation types (coastal dry forest, miombo woodland, teak plantation, pine plantation and cashew plantation) using conventional statistical methods, as well as geostatistics. In the 5 forest types of this study, SOC stocks in the upper 5 cm ranges between 5 (in the cashew plantation) and 13 (in the coastal forest) Mg $ha^{-1}$. The optimal sampling distance for measuring mean SOC stocks varies between 36 m (in the patchy miombo woodland) and 422 m (in the homogenized cashew plantation). Sample sizes fluctuate between 6 and 72 (1 Mg $ha^{-1}$ precision) for respectively cashew plantation and coastal forest. A rectangular grid with a sample interval of 25m can be used for SOC mapping with a point kriging estimation error of 3.0 Mg $ha^{-1}$ in the coastal forest, 2.6 Mg $ha^{-1}$ in miombo woodland, 2.2 Mg $ha^{-1}$ in the teak plantation and 1.1 Mg $ha^{-1}$ in the cashew plantation. Since the pine plantation has no spatial structure; samples can be arranged randomly and its best soil map has an average C content attributed over the whole field. Refining the sampling strategy with a new spatial variability study in other forest types can be based on a regular grid with sampling distances of half the range identified in this study. It was proven that sampling schemes vary strongly because of the different spatial behaviour of SOC in forests and depend on the required precision and research question. Only when the right strategy is followed, high standards of precision can be met without economic loss or risk of statistical misinterpretation.

Besides spatial structures in SOC resulting from vegetation-induced patterns, other factors could locally alter SOC spatial heterogeneity. One such factor in the Tanzanian landscape is the presence of termites and their mounds, which can cover 10% of the soil surface. Termites can influence the soil properties in different ways: they can alter the soil profile development, soil physical properties, soil chemical properties and soil microbiology and have an impact on plant growth. Both increases and decreases in mound OC levels compared to the surrounding soil have been observed, probably depending on termite species and activity status, soil type and land use. Through the impact of termites on different soil properties, termite constructions and especially mounds can be considered as 'islands' in ecosystems where the diversity and quantity of litter transformers, micro-predators and micro-organisms are often different from those in the surrounding soil and where nutrient release can be either enhanced or blocked depending on the age and composition of the structure. These sources of small-scale heterogeneity are increasingly seen to be vital both in the maintenance of biodiversity as in providing farmers with a 'least risk strategy' for crop production. No information was yet available on the termite genera, which occur in southeastern Tanzania, and how they specifically influence SOC on the different typical soils of the region. Therefore a characterization of the spatial patterns of SOC in and around termite mounds in a plot was made in order to adapt sampling strategies to these heterogeneities in the soil. Three different locations were selected which included the typical variation of soil type, altitude and landscape unit of the region. In each location

three plots of 1 ha were selected with 3 common land uses: natural vegetation, crops and a cashew grove. On each plot termite diversity was studied based on the transect method, and SOC was measured in and around different types of mounds and in reference profile pits. Termite diversity decreased from natural forests to cashew plantations and agricultural fields, reflecting the change in canopy cover and resulting effects on soil humidity. Soil feeding genera are most affected by conversion from forest to crops. On the other hand cropping favours many genera known as pests. On average 43 (small) Termitinae mounds and 5 (large) Macrotermitinae mounds are reported per ha. Organic carbon levels of mounds are comparable to those found in literature. OC in the aboveground part of Macrotermitinae mounds (large mounds) are on average 1.5 times higher than the reference micro-pits (0-40 cm). This generally small increase results from the use of saliva in building the mounds as described in literature. Mound carbon contents reflect the amount of SOC in the surrounding subsoil, which is the main building material for Macrotermitinae. OC levels of Termitinae mounds (small mounds) are on average 3.5 times higher than the reference micro-pits, which is the result of incorporation of faeces in the mound material. The increased organic matter is stabilised in the mound through adsorption to the clay fraction. Calculating carbon densities of mounds reveals that on average a Macrotermitinae mound (aboveground) contains 751.8 kg C, while only 0.5 kg C is stored in an average Termitinae mound. Over 1 ha these add up to 21kg OC stored in Termitinae mounds and 3759 kg OC in Macrotermitinae mounds. Thus, although Termitinae raise OC levels much more, due to the small volume of their mounds the effect on field level carbon stocks is much smaller. OC is not only enriched in the mound structures but also under and around mounds. On average the presence of termite mounds and termite-modified soil increases the C density with 12 Mg $ha^{-1}$ or 6%. In Arenosols and Ferralsols this could be of the magnitude of major land use changes, such as conversion from forest to cashew groves. Thus by overlooking the local hotspots created by termite mounds, SOC stocks can be strongly underestimated, and by imprecise sampling of these local heterogeneities, land use change induced increases or decreases of SOC could be obscured. However by taking into account termite induced heterogeneity and by sampling the different landscape components separately, coefficients of variation can be reduced. By using the average ground cover distribution across the landscape, a weighted estimate of SOC can be made. Stratified sampling in and around these mounds is necessary to correctly estimate SOC stocks of these fields, and to be able to distinguish management or land use induced changes in SOC.

# List of abbreviations & symbols

## Abbreviations

| | |
|---|---|
| asl | above sea level |
| BD | bulk density |
| $B_t$-horizon | argic or texture-B horizon caused by clay illuviation |
| C | carbon |
| CDM | Clean Development Mechanism |
| CDM A/R | Clean Development Mechanism Aforestation/Reforestation |
| C/N | carbon to nitrogen ratio |
| DSM | digital soil mapping |
| CEC | cation exchange capacity |
| CF | coastal forest |
| CFC | chlorofluorocarbon |
| Chron. Eon | chronometric eon |
| Cov | covariance |
| CP | cashew plantation |
| CV | coefficient of variation |
| DEM | digital elevation model |
| DSM | digital soil mapping |
| ET | emissions trading |
| FAO | Food and Agriculture Organization of the United Nations |
| FTIR | fourier transform infrared spectroscopy |
| FCCC | Framework Convention on Climate Change |
| frag % | volume of the coarse fragments/100 |
| GDP | gross domestic product |
| GHG | greenhouse gas |
| GIS | geographic information system |
| GLM | General linear model |
| GPS | global positioning system |
| GWP | Global Warming Potential Index |
| ha | hectare |
| HIS | hydroxyl-interlayered smectite |
| HIV | hydroxyl-interlayered vermiculite |
| IC | inorganic carbon |
| IPCC | Intergovernmental Panel on Climate Change |
| ITCRP | Italo-Tanzanian Cashew Research Programme |
| JI | Joint Implementation |
| Kha | kilohectares |
| KP | Kyoto Protocol |
| LCCS | land cover classification system |
| Ln | natural logarithm |
| Log | logarithm |
| LOI | loss-on-ignition |
| LSU | soil-landuse units |
| LUC | land use change |
| LUCC | Land-use and land-cover change |
| LULUCF | land use, land use change and forestry |
| m | mean |
| Max | maximum |
| Min | minimum |
| MIR | mid infrared reflectance spectroscopy |
| MM | Macrotermitinae mound |
| MPE | mean predicted error |
| MW | miombo woodland |
| mya | million years ago |
| NARI | Naliendele Agricultural Research Institute |
| NIR | near infrared reflectance spectroscopy |
| NMR | nuclear magnetic resonance |

| | |
|---|---|
| NPP | net primary productivity |
| OC | organic carbon |
| OM | organic matter |
| SD or s | standard deviation |
| SOC | soil organic carbon |
| SOM | soil organic matter |
| Sp. | Species |
| P | precipitation |
| Pg | peta grammes= $10^{15}$ g |
| PP | pine plantation |
| PSM p | redictive soil mapping |
| ppm | parts per million |
| PTF | pedotransfer function |
| Py-FIMS | pyrolysis-field ionization mass spectrometry |
| RMSPE | root mean square prediction error |
| SDPE | standard deviation of the prediction error |
| SRTM | shuttle radar topography mission |
| TC | total carbon |
| T | temperature |
| Tg | tera grammes= $10^{12}$ g |
| TM | termitinae mound |
| TP | teak plantation |
| TPI | topographic position index |
| UNESCO | United Nations Educational, Scientific and Cultural Organization |
| UNFCCC | United Nations Framework Convention on Climate Change |
| USDA | United States Department of Agriculture |
| Var | variance |
| WB | Walkley & Black |
| WRB | World Reference Base for Soil Resources |
| yr | year |

## Symbols

| | |
|---|---|
| a | range |
| α | significance level anova |
| $C_0$ | nugget |
| $C_0 + C$ | sill |
| γ(h) | semivariogram function |
| Δ | delta, difference |
| h | distance |
| n | number of samples |
| m% | mass percentage |
| $\mu_{\ln}$ | mean of ln transformed data |
| r | Pearson correlation coefficient |
| $R_p^2$ | prediction coefficient of determination |
| $R^2$ | coefficient of determination |
| $\rho_{b,i}$ | observed bulk density |
| $\hat{\rho}_{b,i}$ | predicted bulk density |
| $SOC_{rel}$ | relative SOC content (in %) |
| $\sigma_x^2$ | error variance of variable x |
| $\sigma_k^2$ | kriging variance. |
| $\sigma_{\ln}$ | standard deviation of ln transformed data |
| $\sigma_\varepsilon$ | Kriging estimation error |
| $t_\alpha$ | Student t value |

## Chemical symbols

| | |
|---|---|
| $Al(OH)_3$ | Gibbsite |
| C | carbon |
| $CH_4$ | methane |
| $CO_2$ | carbon dioxide |
| Ca | calcium |
| $CaCO_3$ | Calcite |
| $CaMg(CO_3)_2$ | Dolomite |
| $CaSO_4.2H_2O$ | Gypsum |
| Cr | chromium |
| Fe | iron |
| $FeCO_3$ | Siderite |
| FeOOH | Goethite |
| H | hydrogen |
| $H_2O$ | water |
| He | helium |
| $MgCO_3$ | Magnesite |
| $Mg(OH)_2$ | Brucite |
| $MgSO_4.7H_20$ | Epsom salts |
| $MnCO_3$ | Rhodochrosite |
| $MnO_2$ | manganese dioxide |
| N | nitrogen |
| $NH^{4+}$ | ammonium |
| $NO_3$ | nitrate |
| N2O | nitrous oxide |
| $NaHCO_3$ | sodium bicarbonate |
| NaOH | sodium hydroxide |
| O | oxygen |
| P | phosphorus |

# 1 Soil Organic Carbon

# 1.1 Background

## 1.1.1. What is Soil Organic Carbon (SOC)

Carbon (C) is the fourth most abundant element in the Universe, after hydrogen (H), helium (He), and oxygen (O). This abundance, together with the unique diversity of organic compounds and their unusual polymer-forming ability at the temperatures commonly encountered on earth, make this element the chemical basis of all known life. On Earth, C cycles through the land, ocean, atmosphere, and the Earth's interior in a major biogeochemical cycle. The global C cycle can be divided into two categories: the geological, which operates over large time scales (millions of years), and the biological/physical, which operates over shorter time scales (days to thousands of years) (Figure 1.1).

In this cycle, SOC represents the largest reservoir in interaction with the atmosphere and is estimated at 1600 Pg C to 1m depth (about 2456 Pg C to 2m depth) (Batjes, 1996; Batjes & Sombroek, 1997; FAO,

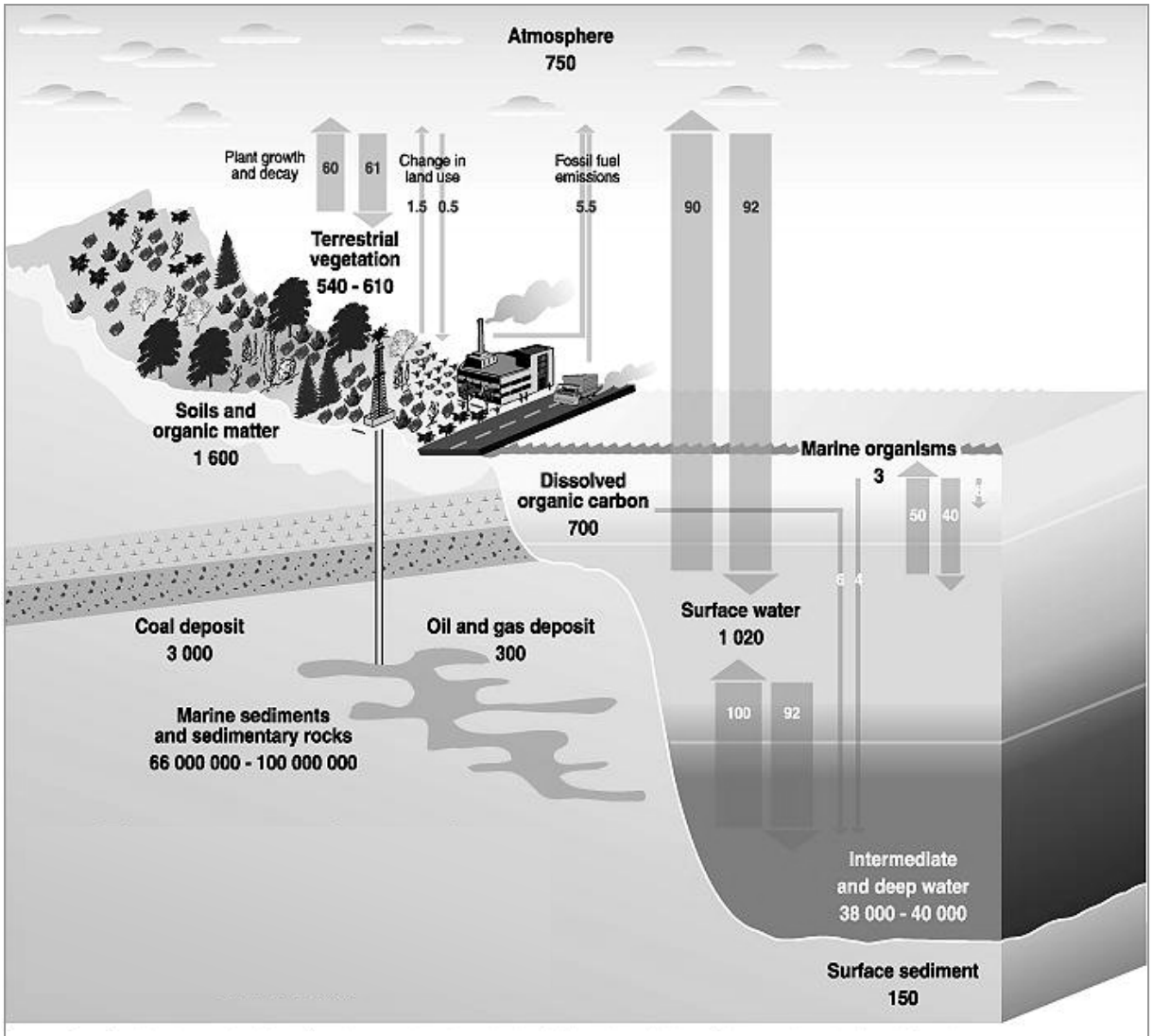



***Figure 1.1 The present C cycle: volumes and exchanges in Pg of C (UNEP/GRID-Arendal, 2000).***

2001). SOC is derived from plants or animals and compounds contain usually carbon and hydrogen along. Soil inorganic C represents about 1700 Pg (FAO, 2001). It is derived from minerals in the earth, for example carbonate C, which is relatively stable unless soils are irrigated or become acidified with increased nitrogen (N).

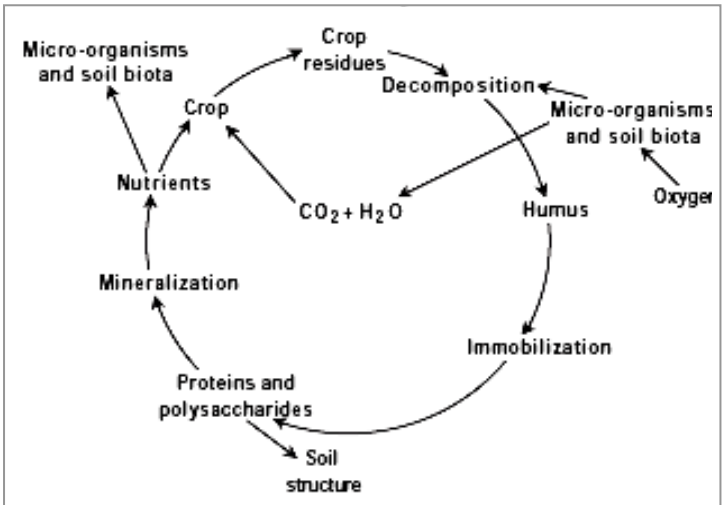



***Figure 1.2 Carbon cycle at field level (IPCC, 2000a).***

The amount of C stored in soil is determined by the balance of two biotic processes: production of organic matter (OM) by terrestrial vegetation and decomposition of OM by soil organisms (Figure 1.2). Each of these processes is strongly controlled by physical, chemical and biological factors. The amount of OM produced depends largely on climatic conditions, soil water status, nutrient availability and plant growth and tissue-allocation patterns. In agriculture and silviculture, these physical and biological factors can be greatly influenced by management practices. The rate of decomposition is controlled by the chemical composition of the OM, soil temperature and water conditions, soil chemical properties (mineralogy, pH, available cations), and soil physical properties (e.g. structure and texture) (Post et al., 2001).

SOC is important for two reasons. Due to the importance of soil in the global C cycle, SOC is an important player in the mitigation of human-induced climate change. As the main component of soil organic matter (SOM), SOC is an important factor of soil fertility.

## 1.1.2. Importance for soil fertility

SOC is the main component of SOM: average estimations vary between 40 (Broadbent, 1953) and 58% (Schulze, 1849; Wolff, 1864). In the broadest sense, SOM consists of diverse components such as living organisms, slightly altered plant and animal organic residues, and well-decomposed organic residues that vary considerably in their stability and susceptibility to further decomposition (Magdoff, 1992). The definition and composition of SOM will be further discussed in Chapter 5. SOM and therefore SOC is important for all three aspects of soil fertility, namely chemical, physical and biological fertility (Batjes & Sombroek, 1997; Reeves, 1997; IPCC, 2000a):

### *1.1.2.1. Nutrient availability:*

Many important chemical properties of SOM result from the weak acid nature of humus. The ability of OM to retain cations for plant use while protecting them from leaching, i.e. the cation exchange capacity (CEC) of the OM, is due to the negative charges created as hydrogen (H) is removed from weak acids during neutralization. When acids or bases are added to the soil, OM reduces or buffers the change in pH. OM may provide nearly all of the CEC and pH buffering in soils low in clay or containing clays with low

CEC (IPCC, 2000a). As SOM is derived mainly from plant residues, accumulated OM is a storehouse of plant nutrients. Decomposition of SOM releases nitrogen (N), phosphorus (P) and a range of other nutrients for plant growth (Sanchez & Salinas, 1982; Schnitzer, 1986; Poss, 1991; Tan, 1994).

#### *1.1.2.2. Soil structure and soil physical properties:*

SOM promotes soil structure and aeration by holding the soil particles together as stable aggregates (Tisdall & Oades, 1982; Robert & Chenu, 1991). Aggregation and C sequestration processes are strongly associated (Golchin et al., 1994; Angers & Chenu, 1998). Moreover, OM intimately mixed with mineral soil materials has a considerable influence in increasing moisture holding capacity (Stevenson, 1994). The quality of the crop residues, in particular its chemical composition, determines the effect on soil structure and aggregation. In the case of erosion, a correlation has been established between the historical decrease in SOM and erosion development (FAO, 2001).

#### *1.1.2.3. Biological soil health:*

As a food source for soil fauna and flora, SOM plays an important role in the soil food web by controlling the number and types of soil inhabitants which serve important functions such as nutrient cycling and availability, assisting root growth and plant nutrient uptake, creating burrows and even suppressing crop diseases (Hendricks et al 1986; IPCC, 2000a). An increase in C sequestration causes an increase in the operational biodiversity and more effective soil biological functioning (FAO, 2001).

#### *1.1.2.4. As a buffer against toxic and harmful substances:*

SOM can lessen the effect of harmful substances such as toxins and heavy metals, by acting as buffers (Robert, 1996) and increasing degradation of harmful pesticides (Tan & Binger, 1986). It also influences the effects of chemical amendments, fertilizers, pesticides and herbicides.

For farmers, soil conservation and prevention of land degradation are increasingly perceived as concrete benefits (Figure 1.3). With higher soil quality, crops will generally be in better health and more resilient. Well-managed agricultural and agroforestry systems present advantages, but there will not always be immediate increases in yield (FAO, 2001). Therefore, in order to achieve a win-win situation, other benefits will have to be added; these can come from various sources such as conventions or policy intervention (Izac, 1997).

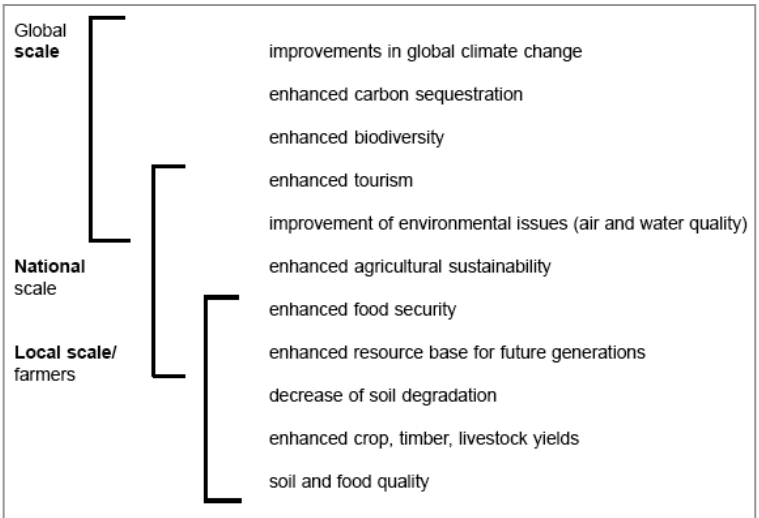



***Figure 1.3 Principal benefits of sustainable soil carbon management at various spatial scales (Izac, 1997).***

## 1.1.3. Importance for the global climate

### *1.1.3.1. Global warming*

Global warming refers to the effect on the climate by human activities, in particular the burning of fossil fuels and large-scale deforestation-activities. These activities are currently leading to the release of large amounts of greenhouse gases into the atmosphere each year (GHGs): about 7 Pg of carbon as carbon dioxide ($CO_2$) together with substantial quantities of methane ($CH_4$), nitrous oxide ($N_2O$) and chlorofluorocarbons (CFCs). The increase in $CO_2$ has contributed about 70% of the enhanced greenhouse effect to date, $CH_4$ about 24% and $N_2O$ about 6% (Houghton, 2005).

The likely impact of climate change on human communities and ecosystems will be complex (Houghton, 2005). Different ecosystems will respond very differently to changes in temperature, precipitation or other climate variables. For humans, the least developed countries are in general most vulnerable; they are likely to experience more of the damaging climate extremes and have less capacity to adapt. A few impacts of climate change will be positive as far as humans and ecosystem productivity are concerned. In some regions, increased temperature will tend to lengthen the growing season or increased carbon dioxide will aid the growth of some types of plants. However, because over the centuries human communities have adapted their lives and activities to the present climate, most changes in climate will tend to produce adverse impacts (Houghton, 2005).
Assessment of the impacts of global warming is also made more complex because global warming is not the only human-induced environmental problem. Loss of soil and its impoverishment (through poor agricultural practice), over-extraction of groundwater and damage due to acid rain are examples of environmental degradations on local or regional scales that are having a substantial impact now (UNEP, 2002). They will tend to exacerbate the negative impacts arising from global warming. The most important negative impacts of climate change include (i) sea-level rise from the thermal expansion of the warming ocean and the melting of glaciers; (ii) changes in the availability, quality and flow of fresh water resources which results in some areas becoming wetter and others drier and in an increased frequency and intensity of extremes such as floods and droughts; (iii) impact on agriculture and food supply through impact on crops, soils, insects, weeds, diseases and livestock, changing crop patterns and an expected yield loss especially in the arid and sub-humid tropics; (iv) effect on natural ecosystems, particularly on vulnerable types of species such as trees and coral, and the unprecedented loss of species and biodiversity and (v) impact on human health because of diminished water availability, food shortages, more frequent floods and droughts, increased spread of insect-borne diseases and heat stress in urban populations (Houghton, 2005).

In the 1970s and 1980s, the attention of scientists and politicians became increasingly directed towards the effects of human activities on the climate (Houghton, 2005). Two important international bodies were created, one in 1988 concerned with science (the Intergovernmental Panel on Climate Change (IPCC)) and one in 1992 with policy (the Framework Convention on Climate Change (FCCC)). Whereas the IPCC focuses on preparing thorough assessments of climate change, its causes and effects, the FCCC recognizes the reality of global warming together with the uncertainties associated with predictions of climate change and states that mitigating action needs to be taken despite the uncertainties. It also points out that developed countries should take the lead in this action. The long-term objective of the Convention is to

achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner. In setting this objective, the Convention has recognized that it is only by stabilizing the concentration of greenhouse gases (especially $CO_2$) that rapid climate change can be halted (UNFCCC, 2009). The Kyoto Protocol (KP) is the first formal binding legislation promulgated under the Convention that commits industrialized countries (known as Annex I countries) to specific reductions in emissions. The KP includes three special mechanisms to assist in emissions reductions by industrialized countries, namely Joint Implementation (JI) that encourages projects that reduce emissions or increase removal by sinks in the territories of other industrialized countries; the Clean Development Mechanism (CDM) that encourages projects that reduce emissions in developing countries (certified emission reductions generated by JI and CDM can be used by industrialized countries to help meet their emission targets); and Emissions Trading (ET) that allows the purchase of 'assigned amount units' of emissions from other industrialized countries that find it easier, relatively speaking, to meet their emissions targets (Houghton, 2005). The CDM is the only mechanism directed specifically at developing countries, the Parties least able to adapt to adverse effects of climate change. Article 3.3 of the KP permits net accounting of direct human induced aforestation, deforestation and reforestation activities in assessing a developed country Party's emissions (UNFCCC, 2009).

Options for reducing the atmospheric concentration of $CO_2$ include reducing future emissions as well as sequestering $CO_2$ that has already accumulated. C sequestration involves 'removing C from the atmosphere and depositing it in a reservoir' (UNFCCC, 2009). C can be sequestered in two major ways: biological and geological. Geological sequestration, which has a fairly large technological potential, has not yet been demonstrated on a scale anticipated to mitigate $CO_2$ emissions and is also more costly (Haile et al., 2008). Biological C sequestrations transfers C (from $CO_2$) in the atmosphere to biomass through photosynthesis and ultimately stores it in plants and soils (Haile et al., 2008). According to the IPCC (2000b), potential increases in C storage may occur in agricultural and forest lands via (i) improved management within a land use, (ii) conversion to a land use with higher C stocks, and (iii) increased C storage in harvested products.

#### *1.1.3.2. The role of Tanzania*

Tanzania ratified the UNFCCC in April 1996. As in most developing countries, emissions from fossil fuel use are low: with 1.18 Tg C Tanzania is 117$^{th}$ in the world ranking (Marland, 2003). However about 90% of all primary energy consumed in Tanzania is biomass-based, in the form of fuelwood, charcoal, and agricultural residues. The land-use change and forestry sector have contributed largely to GHG emissions. Per capita $CO_2$ emissions in 1990 were about 2.2 Mg, of which the land-use change and forestry sector contributed about 95%, the energy sector contributed about 4% and industrial sector contributed less than 1%. $CH_4$ emissions per capita were about 70 g, from combustion of biomass, livestock management, rice production, waste management and coal mining activities. CO and $N_2O$ oxide emissions resulted from biomass burning (CEEST, 1999).

Total emissions evaluation with the Global Warming Potential Index (GWP) indicates that the emissions of $CO_2$ contributed 55% to potential warming due to the 1990 emissions, $CH_4$ provided 44% and $N_2O$

provided 1%. Land- use changes and forestry sector made the largest contribution (53%) towards the warming that may result from the 1990 emissions of trace gas in Tanzania followed by agriculture (33%), energy (13%) and waste management (1%). Industrial processes contributed less than 1% of potential warming (CEEST, 1999).

Since the forest and land-use sectors have such huge impact on GHG emissions, any policies geared to the significant reduction of current and future emissions as well as the sequestration of carbon from the atmosphere should target the forest and land-use sectors (CEEST, 1999).
The most important identified mitigation options in the agricultural, land use and forestry sectors include:

- Maintaining existing stocks through forest protections and conservation; and expanding carbon sinks by means of aforestation, reforestation and enhanced regeneration and agroforestry practices;
- Maintaining or increasing carbon sequestration through better soil management and sustainable agricultural practices;
- Reduce methane and carbon emissions through better practices related to fertilizer application, rice cultivation and loss of organic carbon from cultivated soils (CEEST, 1999).

#### *1.1.3.3. Importance of soils*

For soil C sinks, the best options are to increase C stocks in soils that have been depleted in C, that is, agricultural soils and degraded soils. The global estimates for C sequestration potential in soils range between 1Pg C $yr^{-1}$ (lower figure of IPCC, 1996) and 2 Pg C $yr^{-1}$ (Metting et al., 1999), that is, between one-third and two-thirds of the annual increase in atmospheric C levels (Smith, 2004). The estimates for C sequestration potential in soils are of the same order as for forest trees, which could sequester between about 1 and 2 Pg C $yr^{-1}$ (IPCC, 1996). Over 50 years, the level of C sequestration could restore a large part of the C lost from soils historically.

Soil C sinks resulting from sequestration activities are not permanent and will continue only for as long as appropriate management practices are maintained. If a land-management or land-use change is reversed, the C accumulated will be lost, usually more rapidly than it was accumulated (Smith et al., 1996). For the greatest potential of soil C sequestration to be realized, new C sinks, once established, need to be preserved in perpetuity. Sink strength, that is, the rate at which C is removed from the atmosphere, in soil becomes smaller with time, as the soil C stock approaches a new equilibrium. At equilibrium, the sink has saturated—the C stock may have increased, but the sink strength has decreased to zero (Smith, 2004). The time taken for sink saturation (i.e., new equilibrium) to occur is highly variable. The period for soils in a temperate location to reach a new equilibrium after a land-use change is around 100 years (Jenkinson, 1988; Smith et al., 1996) but tropical soils may reach equilibrium more quickly. Soils in boreal regions may take centuries to approach a new equilibrium. As a compromise, current IPCC good practice guidelines for greenhouse gas inventories use a figure of 20 years for soil carbon to approach a new equilibrium (IPCC, 1997; Paustian et al., 1997).

In the past, opinions differed on whether C sequestration in soils would be a realistic, practical, potentially large-scale option. The current annual emission of $CO_2$-carbon into the atmosphere is $6.3 \pm 1.3$ Pg C $yr^{-1}$. C emission gaps by 2100 could be as high as 25 Pg C $yr^{-1}$ meaning that the C emission problem could be

up to four times greater than at present. Even if the maximum annual global C sequestration potential could be maintained until 2100, soil C sequestration would contribute a maximum of 2–5% toward reducing the C emission gap under the highest emission scenarios. When the limited duration of C sequestration options in removing C from the atmosphere is also considered, it seems that C sequestration could play only a minor role in closing the emission gap by 2100 (Smith, 2008). If atmospheric $CO_2$ levels are to be stabilized at reasonable concentrations by 2100 (e.g., 450–650 ppm), drastic reductions in emissions are required over the next 20–30 years (IPCC, 2000b). However, during this critical period, all measures to reduce net C emissions to the atmosphere would play an important role—there will be no single solution (IPCC, 2000b). Given that C sequestration is likely to be most effective in the first 20 years of its implementation, it should play a central role in any portfolio of measures to reduce atmospheric $CO_2$ concentrations over the next 20–30 years whilst new energy technologies are developed and implemented (Smith, 2004; Smith, 2008). It could be applied regionally or globally only if national or regional soil organizations undertook systematic monitoring by a combination of permanent monitoring sites, well-distributed soil sampling with description of farmers' land management, and remote sensing of land cover (FAO, 2001).

## 1.2 Problem statement and aim

It is clear that SOC represents a key indicator for soil quality, both for agricultural functions (i.e. production and economy) and for environmental functions (e.g. C sequestration and air quality) (FAO, 2001). This thesis will focus on the impact of land use and land use change on $CO_2$ emissions, and on the possible reverse effect of sequestering SOC through enhanced land management.
Global SOC pools are difficult to estimate because of incomplete knowledge of specific soil properties at a global scale (Batjes, 1996), the high spatial variability of SOC (Bird et al., 2002) and the different effects of the factors controlling SOC (Côté et al., 2000). Thus, regional and national scale studies of SOC are necessary to refine global estimates (Post et al., 2001; Bernoux et al., 2002). Both soil and land use data should be used in determining regional SOC. While soil factors are important, as are climatic factors, in explaining C storage or pools over long periods of time, changes in vegetation or land use determine the changes in C sequestration over shorter periods (FAO, 2001).

Since tropical soils store 26% of the SOC stocks of the world they could serve as C storage reservoirs (Batjes, 1996). Veldkamp et al. (2003) reported that although SOC concentrations are low in highly weathered tropical forest subsoils, the total stock is significant due to the soils' large worldwide volume. As the reliance on marginal lands for food production increases, there will be an increasing need for developing sustainable systems to maintain and improve the OC content and nutrient supply in the soil, and to avoid land degradations (Batjes & Sombroek, 1997). Particularly in semiarid and sub-humid Africa where severe soil degradation and desertification are related to perpetual food crises and overall impoverishment, soil C sequestration represents a development strategy with high potential (Vågen et al., 2005).

To be successful, soil C sequestration projects and activities will need to have a strong sustainable development component, so that the project improves the livelihood of farmers by improving agricultural productivity, reducing the risk of crop failure and providing access to better agricultural inputs. Soil C

sequestration efforts are more likely to succeed if they build upon existing institutions, initiatives and organizations. Necessary funds needed for C sequestration projects in developing countries could be found in the Clean Development Mechanism of the Kyoto Protocol. In this way C sequestration opportunities could go hand in hand with local conservation of natural resources as well as poverty alleviation (Madlener et al., 2006). However, the KP limits reporting of C sequestration activities to those that are both "measurable and verifiable". Even if allowed as part of an accounting system, credit for C sequestration activities could be withdrawn if high standards of measurement cannot be met (UNFCCC, 2007). Tools for monitoring, verification or certification will be needed in developing countries in order to measure the changes in C pools in relation to soil type, climatic conditions, land occupation and different land management practices (FAO, 2001). Present and past land occupation and agricultural practices have to be documented. Remote sensing will be a very useful tool to extrapolate the results and map the vegetation cover and land use together with real, measured data on the changes in soil C stocks (FAO, 2001). The feasibility and sustainability of C credit schemes will depend on appropriate measuring and monitoring schemes, which are rapid, feasible and cost-effective.

Southeastern Tanzania serves as a typical example of soil degradation and SOC losses through land use change, deforestation and increased land pressure in the tropics. Over the last 40 years population increase and migration induced a high land pressure and the replacement of bush land and woodland by agricultural land. Estimations of the deforestation rate in Tanzania range between 300.000 and 600.000 ha $yr^{-1}$ in the 1980s (Makundi & Okiting'ati, 1995). In Southern Tanzania SOM from uncultivated areas decreased by on average 50% after 25 years of cereal cropping (McDonagh et al., 2001). Local institutions have shown their interest in tackling these problems and in implementing soil conservation management measures (Topper & Kasuga, 2003), for example the reforestation of the steep escarpment bordering the plateaus. A possible extension of Rondo Forest (Lindi Region) with 60,000 ha for C sequestration has already been proposed (Ahlback, 1986, CEEST, 1999).

From this overview it is clear that regional studies on the relationship between SOC, land use and land use change in the tropics are needed. Severe land use changes in the past make southeastern Tanzania a good example. A strong demand for reversing land use change induced land degradation, C losses and losses of soil fertility exists in this region. A regional SOC study will be a necessary addition to more general global C estimations. However in order to be measurable and verifiable, SOC measuring techniques have to be both cost efficient and reliable, and have to be adapted to the specific spatial variation of SOC in this region.

The general research questions are:

- How big is the SOC stock under different soils and land uses of southeastern Tanzania?
- Which land uses or soils offer potential for soil C sequestration?
- How can SOC measurements be optimized for this region?

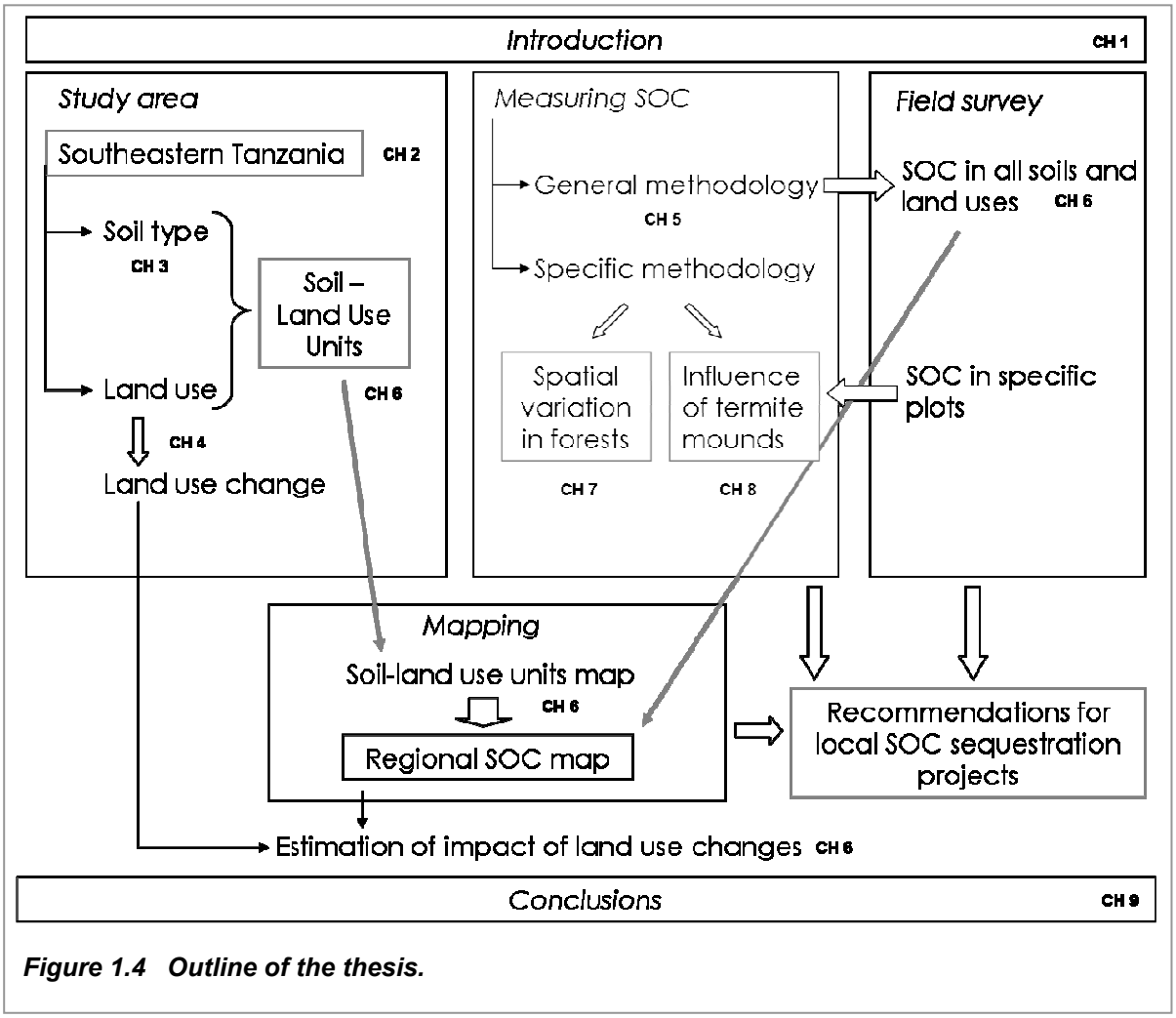



***Figure 1.4 Outline of the thesis.***

The steps that will be taken to answer these questions are outlined in Figure 1.4**,** which is based on four main pillars: study area, ways of measuring SOC, field surveys and mapping. Chapter 2 will start with the description of the study area, southeastern Tanzania. The most important part of the study area for a soil study is a regional soil map. However, no useful soil map was available of this area; therefore Chapter 3 discusses the drawing up and description of an updated soil map. Since mapping of SOC is ideally based on the combination of a soil and land use map, in Chapter 4 the present land use of the study area is discussed, as well as land use changes that have occurred in the past. Before starting to measure SOC in the different soils and land uses of the region, it is wise to reflect on the methodology of measuring SOC. Different techniques for measuring SOC have been used in the past, which makes it difficult to compare datasets. In Chapter 5 these techniques are thoroughly discussed and compared. Now that we have an understanding of the various soils and landscapes in the area, and we know how to measure SOC, a field survey makes clear how much SOC can be found in every land use for every soil of the region (Chapter 6). Based on the field survey, the soil and land use map, a regional SOC map is created. The effect of land use changes on the SOC pool is also assessed. Based on the SOC map, estimations can be made for the total C stock of the region, and recommendations can be made on which areas are more interesting for sequestering SOC than others (Chapter 6). If SOC sequestering in forests is favourable in certain areas, reforestation might be considered. However, the effect on SOC has to be measurable and verifiable. Sampling schemes for SOC in forests, which are both cost efficient and reliable, are discussed in Chapter

7. Chapter 8 will discuss another typical feature of this landscape, which could influence spatial patterns and therefore sampling schemes for SOC: termite mounds. Finally, recommendations can be formulated for local farmers and land use planners, who can then decide whether land use change will impact the SOC stock of a field in a certain landscape. Our experience in sampling strategies can help them choose the right sampling scheme, which is not only cost efficient but which can also detect differences in a reliable way.

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# 2 Description of the Study Area

# 2.1 Physical environment

## 2.1.1. Location and administrative framework

The study area of 415 Kha is situated in Southeast Tanzania. Southeast Tanzania coincides with the mandate area of Naliendele Agricultural Research Institute (NARI), which is defined as Mtwara and Lindi Region and the district of Tunduru in the Ruvuma region. Tanzania is divided into 25 regions, which are the largest administrative units of Tanzania (see inset of Figure 2.1), hierarchically followed by districts, divisions, wards and villages or towns at the lowest level (Bennett et al., 1979a). The study area, which was selected for this thesis, consists in the whole of this mandate area, except for the most northern part of Lindi region and Tunduru district (Figure 2.1). This study area is representative for all types of soils, land uses and landscapes of Southeast Tanzania. It is bordered by the Mavuji River in the north, Lumesule River in the west, Ruvuma River, which is the border with Mozambique, in the south and the Indian Ocean in the east.

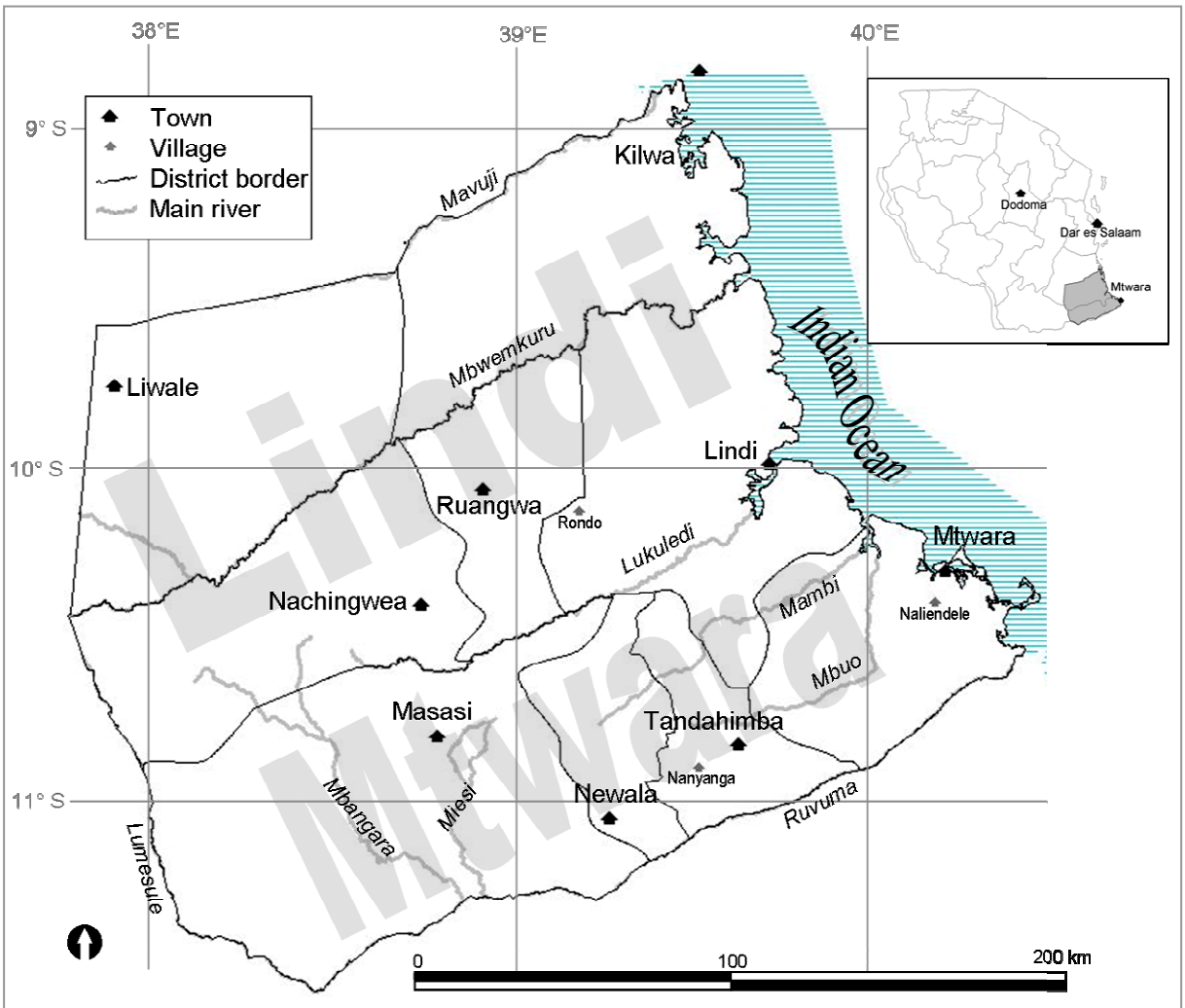



***Figure 2.1 Study area in Mtwara and Lindi regions, with the districts and their capitals (bearing equal names), main rivers and some villages important for this study. Inset: Tanzania with its regions and the location of the study area.***

The most important town of southeastern Tanzania is Mtwara. Mtwara was first developed after WWII by the British as part of their East African groundnut scheme, a project aimed at alleviating the post-war shortage of plant oils through the implementation of large-scale groundnut production at various sites in the region. Although the groundnut scheme soon failed, Mtwara's port continued to play a significant role in the region over the next decades as an export channel for cashew, sisal and other products (Fitzpatrick, 2000). The region has long been neglected by the government, and infrastructure – in particular the road network – is undeveloped. The population of Mtwara town counts about 100.000 inhabitants (URT, 2002).

## 2.1.2. Landscapes, geology and soils

From east to west, southeastern Tanzania can be divided into a coastal area, an area of plateaus and floodplains, a central area of plains and a western area of plateaus and uplands (Figure 2.2). The area is drained to the Indian Ocean by mostly seasonal streams. The major rivers have a south-west north-east direction (Figure 2.1).

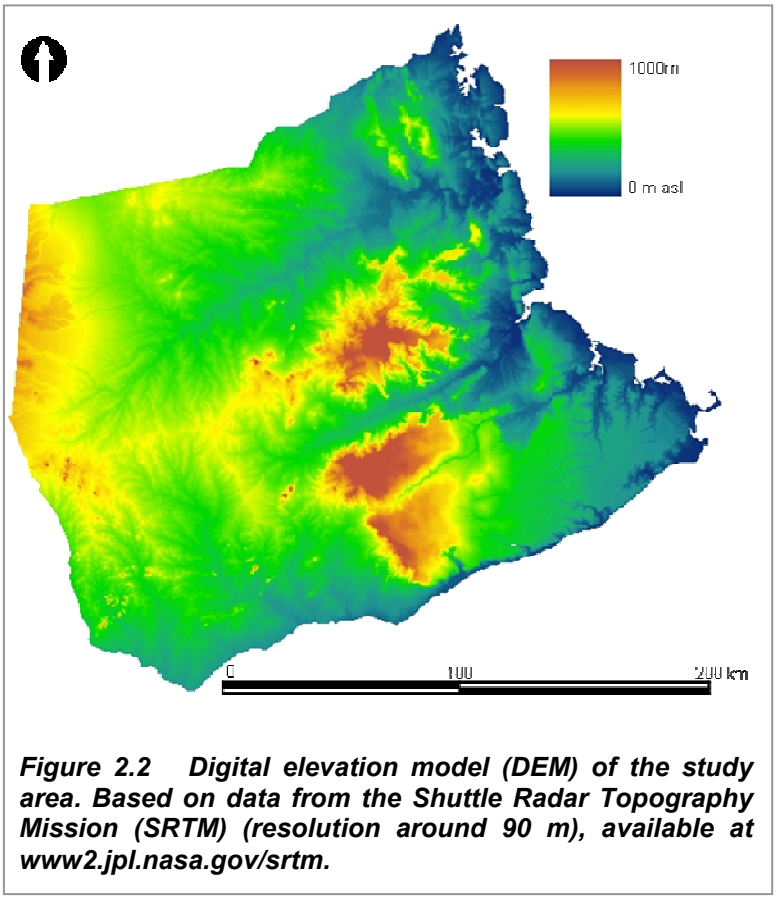



***Figure 2.2 Digital elevation model (DEM) of the study area. Based on data from the Shuttle Radar Topography Mission (SRTM) (resolution around 90 m), available at www2.jpl.nasa.gov/srtm.***

The geology of the area was described in detail by Kent et al. (1971) and Bennett et al. (1979a). It consists of old basement sediments with a series of younger deposits. The basement zone consists of the oldest rocks in the area, of the Archean period. Deep sediments infilling a geosyncline were subjected to regional metamorphism with granitisation and magmatisation; producing mainly hornblende and biotite gneisses and granulites. As a result of relative fluctuations of land and sea levels and recurrent marine transgression and regression, the land surface is built out of deposits in successive periods being laid down parallel to the shore. The main periods and modes of deposition appear to have been as follows (Figure 2.3):

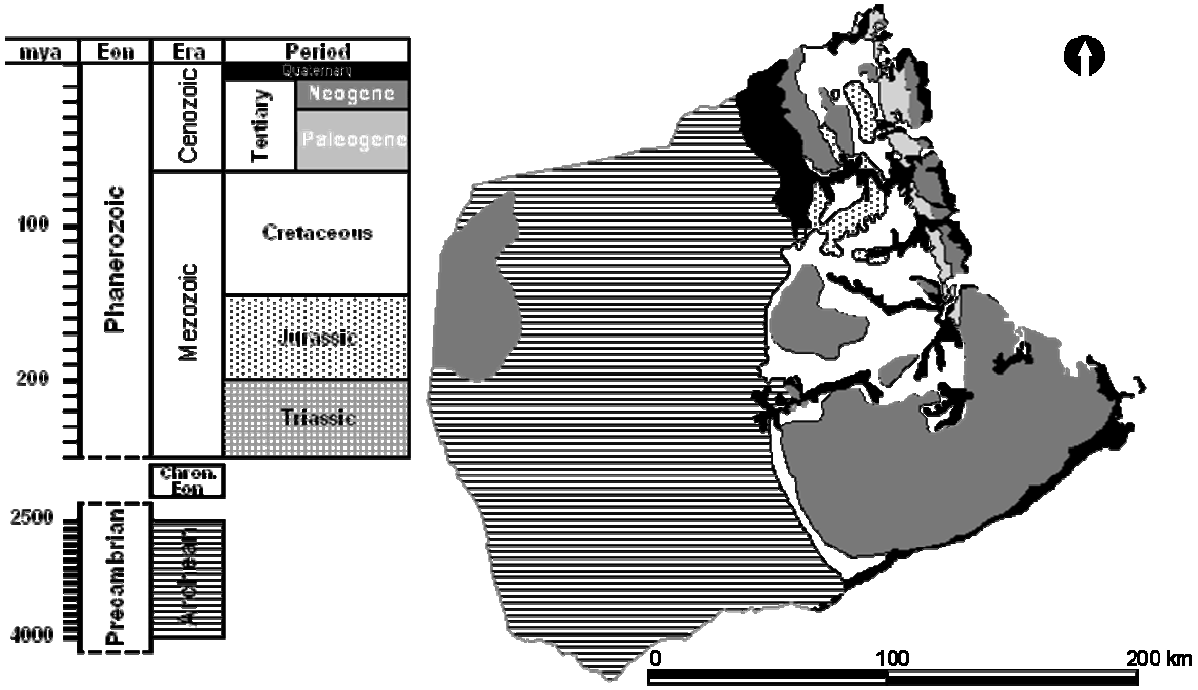



***Figure 2.3 Geology of the study area (derived from Kent et al., 1971 and Bennett et al., 1979a).***

1. Quaternary: a marine coastal fringe deposition and local riverine and lacustrine alluvial formations.
2. Upper Tertiary (Neogene): a marine transgression in the Miocene laid down a mixture of clastic and non-clastic sediments. Subsequent post-Miocene regression is related to terrestrial deposition of arenaceous sediments;
3. Lower Tertiary (Paleogene): a marine deposition of grey clays, marls and limestones;
4. Upper Cretaceous: a marine deposition of grey clays and marls on the eastern edge of the lower Cretaceous formation;
5. Lower Cretaceous: a predominantly terrestrial arenaceous deposition during a marine regressive phase;
6. Jurassic: a marine deposition of limestone and various clastic sediments;

The region can also be divided in land units. A land unit, as defined by Bennett et al. (1979a) is the smallest area of land, identified and described in terms of environmental relationships (Figure 2.4). The landscapes and land-units of the target area will be discussed briefly, based on Bennett et al. (1979a), Ngatunga (2001) and Dondeyne et al. (2003). A more detailed description of the soils in the land units will be given in Chapter 4.

### The coastal area:

This area is adjacent to the Indian Ocean and comprises coastal plains, coastal hills and coastal dissected plains. The coastal plain is a narrow, low lying land (roughly 10-20 km in width) running from the north (Kilwa district) to the border with Mozambique in the south, which is mostly below 100 m asl. It consists of marine Quaternary and Neogene deposits of coral limestone and clayey or sandy sediments. A chain of

hills runs parallel to the coast west of the narrow coastal plain and extends 5-15 km inland and northwards of Lindi town. These hills rise to an altitude of 300m asl but the altitude decreases in the north where it hardly rises above 75 m asl. The geology consists of Paleogene and marine Neogene deposits mostly limestone and marls. The coastal dissected plain lies west of the hills and extends in north-south direction from the border with the Coast Region in the north to the northern border of the Makonde dissected plateau. Streams to the west dissect this plain, which is wider in the north (20 km) and narrows down the south. Geology consists of Cretaceous marine deposits of clays, marls, mudstones and shales.

### The eastern plateau area:

The eastern plateau area is located west of the coastal area and extends from the north (Kilwa Uplands) to Rondo or Lindi Plateau (middle) and finally to the Makonde plateau (close to the border with Mozambique) in the south. These plateaus are flat topped, but locally deeply dissected and have steep scarps, often 300 to 400 m high. The plateaus tend to restrict the drainage of the major rivers giving rise to large alluvial floodplains. With a width of about 40 km, the Kilwa Upland, which rises to about 500m, asl, is narrowest of the three eastern plateaus. The Rondo plateau is about 80 km wide and is the highest (870 m asl) of the three eastern plateaus. The Makonde plateau is about 140 km wide and reaches about 800m asl at its highest point. It is divided into the eastern Makonde Dissected plateau (120-350m) and the

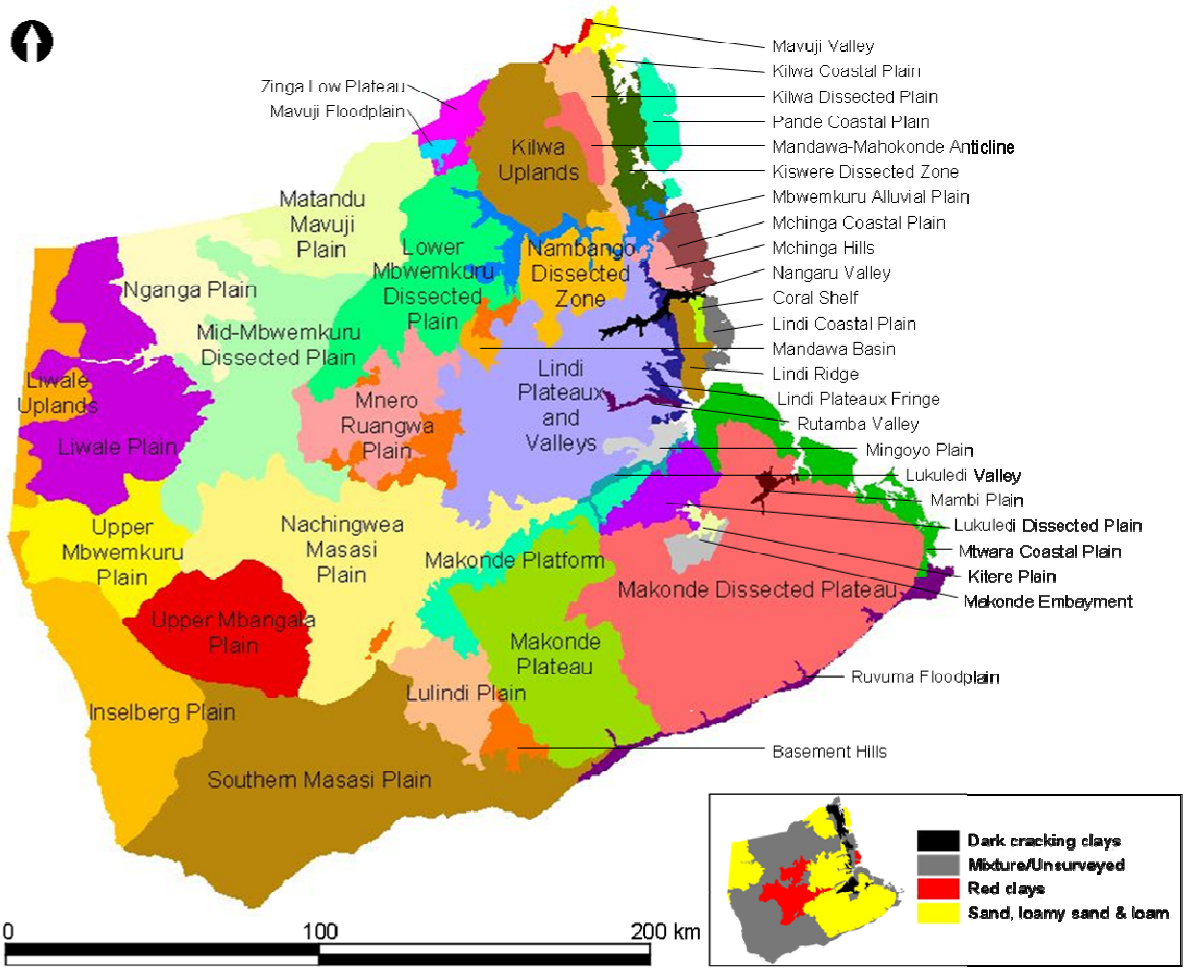



***Figure 2.4 Land units of the study area as defined by Bennett et al. (1979a) and their associated texture group.***

western Makonde high plateau (350-800m asl). The geology is terrestrial lower Cretaceous with continental Neogene sandstone deposits. River valleys that dissect the plateaus have floodplains consisting of Quaternary alluvial deposits or, locally, of lacustrine and marine deposits as the Kitere and Mambi plains.

**The central plains area**

The inland plains are gently undulating with broad flat-topped interfluves and wide shallow valleys. Due to uplifting of the western sedimentary area, erosion processes dissected part of the plains. Geologically the plains in Masasi and Nachingwea districts belong to the Precambrian Basement zone while the Liwale plains fall under the western sedimentary zone. The altitude ranges between 75 and 450m asl. These plains are famous for isolated inselbergs that are more common in the south and less and smaller in size and height in the north, with the highest reaching 800m close to Masasi town. Rocky hills, the basement hills, are also found in the eastern part of the plains adjacent to the Rondo and Makonde Plateau. They are mostly gneisses, although west of Newala quartzite seems to dominate.

**The western plateau and upland area**

The western area consists of Liwale uplands. It is a complex of flat plateaus, sloping, slumped and dissected plateaus and highly dissected terrain of ridges and valleys. The uplands consist of sandstone of the Karoo age, overlying basement rocks.

## 2.1.3. Climate

Climatic conditions (rainfall and temperature) of the main towns and some important villages, spread over the different land units, are given in Figure 2.5. Climatic conditions in Mtwara and Lindi regions are influenced by two major airstreams, the southeast tradewinds in mid-year and the northeast tradewinds during the turn of the year. The weather pattern is conditioned by movements of the equatorial trough (Bennett et al., 1979a).

Temperatures vary little, the average temperature of this locations being 21.8°C in July and 25.5°C in November-December. The mean annual temperature at the coast is above 26°C, on the plateaus it is around 22-23°C and in the inland plains around 24°C (Figure 2.5). Diurnal differences are also slight, although sometimes they can be greater than average mean differences, particularly where altitude acts as a modifying factor to climate (Bennett et al., 1979a). Mean annual rainfall in the study area ranges between 726 mm $yr^{-1}$ (Nachingwea district) and 1162 mm $yr^{-1}$ (Liwale district).

The rainfall pattern is uni-modal, but very erratic. A dry spell of one or two weeks often occurs at the end of January or at the beginning of February. Rainfall is higher on the plateaus (e.g. 1035 mm $yr^{-1}$ in both Lindi and Newala). The central plains, which are on the rain shadow side of the Makonde and Rondo plateaus (Bennett et al., 1979a), have a distinct drier climate (Figure 2.5). On average, the rainy season starts in December, when rainfall is greater than half the reference evapotranspiration, and persists till April or May (Dondeyne et al., 2003).

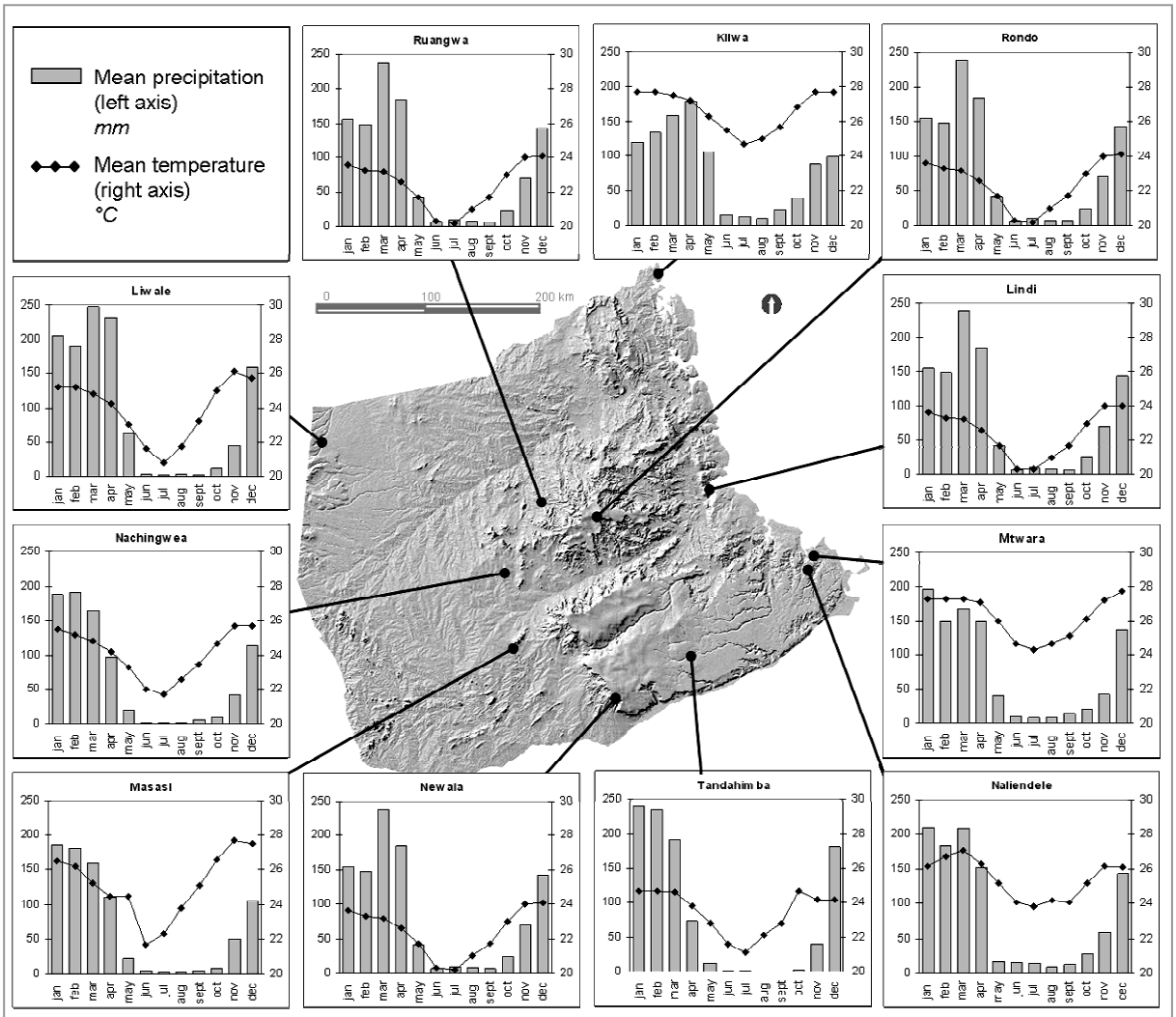



***Figure 2.5 Mean precipitation and temperature data for the important towns and villages of the study area. Climatic data of stations and interpolations from New LocClim (FAO, 2005).***

# 2.2 Socio-economic environment

The coastal zone is a dynamic area surrounding the interface between land and sea. Most coastal activities in Tanzania rely on the natural resources that the coast offers. Therefore, the condition of coastal ecosystems and social well-being are closely linked. A decline in coastal ecosystem productivity has a direct negative impact on society. In nature, coastal systems maintain a dynamic equilibrium. Human activities, if left unchecked, can threaten this sensitive equilibrium, and undermine the productivity of the resource and the very foundation of current and future livelihood opportunities (Wagner et al., 1998).

## 2.2.1. Population and people

The population of Mtwara region amounts to 1,128,523 and that of Lindi region to 797,306 (URT, 2002). With its 68 inhabitants per square kilometre Mtwara is one of the densest populated regions of Tanzania, while Lindi is one of the least populated (12 inhabitants per square kilometre) (URT, 2002). Population growth rate measures 2.0% in Lindi and 1.4 in Mtwara (URT, 1988). The region is known for its low level

of development including poor communications, unsafe water supplies, poverty, traditional belief systems, lack of education, poorly run health services and malnutrition (Wagner et al., 1998). The life expectancy is 46 for males and 48 for females and infant mortality rate (12%) is highest among all regions of Tanzania. Lindi and Mtwara are also amongst the regions with the highest percentage of children underweight (Wagner et al., 1998).

The largest tribe in the study area is the Makonde, followed by the Mwera. Other tribes include the Makua, Matumbi, Yao, Mawia Ngindo and Machinga (Bennett et al., 1979b).

The Makonde people originated in northern Mozambique, where many still live. At the beginning of the 18th century, large numbers of Makonde began to migrate northwards across the Ruvuma River and up the coast, as well as onto the Makonde Plateau around Newala. It is likely that some of these migrations were undertaken to escape flooding in the Ruvuma valley. More followed in the 19th century, seeking relief from famine in Mozambique and refuge from the raids of slave traders. The Mozambican war sparked another large influx, with up to 15,000 Makonde crossing the border during the 1970s and 1980s in search of a safe haven and employment. While some returned following the 1992 peace accords, many stayed and have now become integrated into Tanzanian life. In Tanzania, apart from a carving community in Dar es Salaam, most Makonde have settled in Mtwara, Newala and Lindi districts, with the largest concentrations on the Makonde Plateau. Although the Makonde on both sides of the Ruvuma river are considered to be a single ethnic entity, there are numerous cultural and linguistic differences between the two groups. The Makonde, like many tribes in the southeast, are matrilineal. Although customs are gradually changing, children and inheritances normally belong to the woman, and it is common for husbands to move to the village of their wives after marriage. Most of them are either Muslim or Christian (Catholic, Lutheran, Evangelical), many practise their traditional religion as well. Settlements are widely scattered – possibly a remnant of the days when the Makonde sought to evade slave raids, and there is no tradition of a unified political systems. Each village is governed by a hereditary chief and a council of elders. Most Makonde are subsistence farmers, and there is speculation as to why they chose to establish themselves on a waterless plateau. Makonde means 'dry areas', and there is a singular form Likonde, which is also the name of several villages on the plateau. Possible factors include the relative safety that the area offered from outside intervention (especially during slave trading days), and the absence of the tsetse fly (Fitzpatrick, 2000).

### 2.2.2. Economy, agriculture and forestry

Over the period 1980-1994, Mtwara region contributed 3.3% of the national GDP and Lindi 2.0%, which is amongst the smallest of all regions. With a GDP per capita of 108 US$ in Mtwara and 69 US$ in Lindi these regions are ranked nationally among the poorest (Wagner et al., 1998).

More than 98% of the population is engaged in agricultural production (small-scale farming). The traditional farming system in Mtwara and Lindi regions is one of manual peasant agriculture with very few cash inputs, producing for subsistence and a sizeable cash surplus. The large majority of the farms are individual fragmented holdings; collective farms occupy a very small area. The greater part of the cultivated area is rainfed, but many villages also utilize groundwater in the more fertile valley land (Bennett et al., 1979b).

The Forestry sector contributes significantly to the economy of Tanzania. Forestry and Wildlife are estimated to contribute about 3.3 per cent to the GDP and about 10 per cent of the country's registered exports (URT, 1989). However, the sector's real contribution is grossly underestimated because there is substantial unrecorded consumption of wood fuels in the rural areas. In addition, the value of other forest products, traded informally, is not taken in account (Dallu, 2003). The forestry sector provides 730,000 person years of employment (Ngaga, 1998). Bio-energy consumption is estimated to account for more than 92 per cent of the total energy consumption in Tanzania (Dallu, 2003). In Mtwara and Lindi forest, timber is mainly used for firewood and the production of charcoal (Wagner et al., 1998).

Different types of natural forests as well as secondary vegetation can be found in the study area. However, forests in Tanzania are under high pressure of human activities such as harvesting of fuel wood and charcoal and changes in land use (FOSA, 2000). In Mtwara and Lindi, forests are mainly cut to clear land for low input, extensive agriculture (Wagner et al., 1998). Along with the growing population, this pressure will continue to grow. By changing the economic climate, the government tries to stimulate private investments in plantation forestry to meet the future demand for wood fuel and also for the long-term supply for wood-based industries. On the other hand, the government tries to involve local communities in sustainable forest management. The overall goal is to establish a sustainable forestry that offers a firm contribution to the national economy and decreases the poverty, which is often the basic cause of forest degradation (FOSA, 2000).

Livestock are yet relatively unimportant, fowl and small stock being kept most widely (Bennett et al., 1979b). Fishing is the major livelihood and source of income for inhabitants of coastal villages. Most of the catch in coastal regions is from the artisanal fishery using traditional techniques. Fresh water fishing is carried out in lakes and large coastal rives with small boats. In specific locations in Mtwara region, dynamite fishing has affected fish abundance and catch (Wagner et al., 1998).
Small-scale mining offers an opportunity to increase income in coastal regions. Known mineral deposits in Mtwara are amongst others rhodolite, sapphire, amethyst, graphite and marble. Minerals with potential for exploitation in Lindi are gold in Nachingwea and common salt along the coastline (Wagner et al., 1998).
Coastal tourism is growing, although much of its potential is underdeveloped. There is very little industry in the Lindi and Mtwara regions; cashew-processing plants are the most important. Other income generating activities include wage labour, trading and craft (Ngatunga, 2001).

Since 2007, gas has been exploited in Mnazi Bay. This will gradually provide the region with a more reliable energy supply, and thus enhance the local economy. The recent opening of the renewed road to Dar es Salaam is expected to have a strong impact on import and export as well as on local tourism. Although roads are the most important means of transportation within and among regions, the road system in general is in extremely poor condition. In rural areas, the bicycle is the main form of local transportation. Beside the large port in Mtwara, small local ports exist in Lindi and Kilwa. The major airport is in Mtwara. There are no railways in Mtwara and Lindi regions (Wagner et al., 1998).

# 2.3 Soil research

Most agricultural research in this region was conducted by the Naliendele Agricultural Research Institute (NARI), which is subsidized by the Ministry of Agriculture and Food Security of the Government of Tanzania.

## 2.3.1. Available information

Important studies contributing to the knowledge of soils and land use are amongst others Bennett et al. (1979a, 1979b), ITCRP (1981), NSS(1987), Ngailo & Kips (1991), Kips & Kimaro (1993), Verwilgen (1996), Wijffels (1997), Cools (1998), Dederen (1998), Majule, (1999), Ngatunga (2001), Dondeyne et al. (2003), Dondeyne (2004), Kafiriti (2004) and Tenga (2006).
Not only the articles, theses and reports of previous research are important, but also the databases with soil and land use information. For this study, three datasets were selected for their important soil profile descriptions. In the scope of this research, we conducted an additional soil survey in 2005, which completed the soil dataset.

**1) Bennett et al., 1979a & 1979b**

In 1979, Bennett et al. made a report on natural resources, physical environment, agriculture and development prospects of Mtwara and Lindi regions as a base for regional development planning. It comprises the first elaborate soil study of the region and describes geology, landform and soils based on transects within land units or across unit boundaries. These land units were already presented in Figure 2.4. A total of 634 auger holes was made along 140 transects. Soils were examined and 40 soil profiles were sampled and analysed. Soil features were described in detail for every land unit.

**2) ITCRP, 1981**

The scope of the Italo-Tanzanian Cashew Research Programme was the identification of possible causes for production decrease of cashew. One of the outcomes of this study was a soil map of the region, based on 210 full soil profile descriptions and analyses.

**3) Ngatunga, 2001**

A study was carried out by Ngatunga in 2001 on the effect of sulphur dusting on soils and intercrops. It includes 30 full profile descriptions.

**4) New dataset, 2005**

During a regional survey in 2005, the author sampled 354 new profiles from 88 villages. Details on survey and sampling will be given in Chapter 5. Descriptions include full physical profile descriptions, SOC and bulk densities (BD) at 0 and 40 cm, GPS coordinates current land use and land use history, site management and environmental conditions. Chemical characteristics were derived from nearby comparable profiles from the dataset and soils were classified according to the key of World Reference Base (WRB) (FAO, 2006).

These four datasets will be used in Chapter 3 as a base for a renewed soil map, in Chapter 4 for classification of the land use and in Chapter 5 and 6 for calculating SOC stocks in soils and determining relationships between soil type, land use and SOC.

### 2.3.2. Framework of this research

This research was conducted under the Soil Conservation Management Project, which is a collaborative research project between the NARI and the KU Leuven; funded by the Belgian Agency for Development Co-operation through the Flemish Inter-University Council. The main goal of the project was to contribute to the development of sustainable land management practices in southeastern Tanzania with special attention to soil conservation techniques. Specific objectives were:

- To understand land degradation processes in the study area and their controlling factors, with particular emphasis on the role of human factors.
- To build capacity in soil conservation at NARI and in the Regional extension offices.
- To identify the optimal soil conservation measures, tailor cut to different land user categories to solve on-site and off-site land degradation issues.
- To provide a stakeholder analysis of land degradation, increase public awareness and promote bottom-up solutions to the problem.

A distinction was made between (1) physical land degradation by landslides and gully erosion, sheet and rill erosion and (2) chemical land degradation with, amongst others, soil fertility status as reflected in the soils C status.

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# 3 Soil Scape Map of Southeastern Tanzania

# 3.1 Introduction

In the previous chapter, it has been stated that the study area consists of many different landscape units, with different geology and topography, which results in a variety of soil types. Mapping and upscaling of SOC in the study area will be based on soil and land use maps. The first step will be the creation of a soil map of the study area, in the next chapter a land use map will be produced.

# 3.2 Overview of available soil maps

Several national and regional soil maps were created for Tanzania with scales from 1:1,000,000 to 1:3,000,000 (Kauzeni et al., 1993). An early soil map of Tanzania distinguished eluvial and illuvial soil types and several catenary associations and soil complexes (Carlton, 1954). In Andersons national soil map, (1967) soil classes used by d'Hoore (1964) were adopted, e.g. ferruginous soils and ferrisols. Baker (1970) on the other hand used soil classes indicating geological origin, e.g. alluvial lacustrine soils and gneiss origin soils. A soil survey based on aerial photography techniques was attempted in 1967-1968 by the American Peace Corps (published in Hathout, 1983). Hathout (1975, 1983) published a soil map of the country based principally on soil texture and drainage conditions related to soil orders of the USDA Seventh Approximation (the precursor of Soil Taxonomy) (SSS, 1960). A national soil map based on the FAO/UNESCO legend was produced by Samki (1977). These maps give a good indication of the soil distribution in the country, but are too small-scaled for a regional study.

An important regional soil study was conducted by Bennett et al. (1979). It comprises the first elaborate soil study of the region based on 634 auger holes along 140 transects (see paragraph 2.3.1 and Figure 2.4). Soils were grouped and mapped based on their texture and origin and classified according to FAO-UNESCO (1974) as follows: dark cracking clays on marine marl (Pellic/Chromic Vertisols), dark cracking clays on riverine and lacustrine alluvium (Pellic/Chromic Vertisols), red clays on basement rocks (Ferralsols, Cambisols, Dystric/Eutric Nitisols, Ferric Acrisols/Luvisols), red clays on limestone (Ferric Luvisols), sands, loamy sands and sandy loams on terrestrial sediments (Rhodic/Xanthic/Orthic Ferralsols, Ferralic Arenosols, Ferralic Cambisols, Ferric Acrisols, Gleyic Cambisols), sands, loamy sands and sandy loams on marine sediments, sands, loamy sands and sandy loams on basement rocks and undifferentiated soils on basement rocks (Ferric Luvisols, Gleyic Luvisols). Although the descriptions of the soils within the landscape units are precise and rather complete, soils were only arranged in large groups and they were not determined in detail according to the WRB (World Reference Base for Soil Resources) (FAO, 2006).

Another regional soil map was developed by the Italo-Tanzanian Cashew Research Programme (ITCRP, 1981) (Figure 3.1). The scope of the program was the identification of possible causes for production decrease of cashew. One of the outcomes of this study was a renewed and refined soil map of the region, based on 210 full soil profile descriptions and analyses and classified according to FAO-UNESCO (1974). Although this map is commonly used as a base for other regional agricultural and land use studies, it has been proved to contain a number of inaccuracies on the type and extent of soils. For example, most of the Makonde plateau is mapped as Cambic Arenosols, while Dondeyne et al. (2003) found mainly Acric

Ferralsols. None of the soil profiles described by Ngatunga (2001) which are situated in the Ferric Luvisol area of the ITCRP map are defined as such. Moreover, soils under forest or game reserve were excluded from the study.

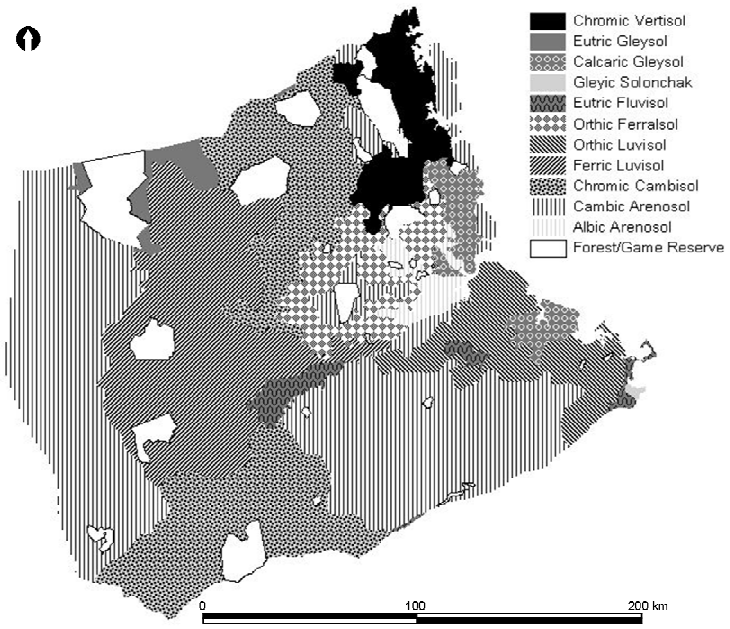
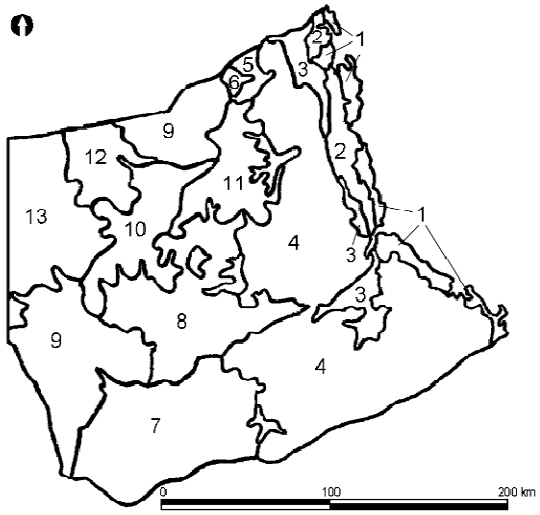



***Figure 3.1 Soil classification of the study area, based on the soil map by the ITCRP (1981).***

De Pauw (1984) made a study on soils, physiography and agroecological zones of Tanzania in the framework of the crop monitoring and early warning systems project. Based on mainly soil survey reports and maps, geological maps and literature he made a state-of-the-art of the soils of Tanzania (Table 3.1). Although the classification system gives precise information on the occurrence of different soil types within soil units, the soil map is not available based on a classification system such as WRB (FAO, 2006), although a conversion table between the soil descriptions and possible soil classes of FAO-UNESCO (1974) is offered.

***Table 3.1 Soil units and soil types of the study area, based on the soil map by De Pauw (1984).***




| Soil unit | Dominant soils (>50%) | Associated soils (15-50%) | Inclusions (<15%) |
|---|---|---|---|
| 1 | m | o, p | b, d, i , j |
| 2 | p | h | a |
| 3 | n | o | - |
| 4 | b | - | m, o, s |
| 5 | k | m | - |
| 6 | - | r, s | q |
| 7 | b | c, g | - |
| 8 | e | k, l | |
| 9 | f | k, l | g, o |
| 10 | c | e, b | p |
| 11 | - | c, f | p |
| 12 | k | - | h |
| 13 | b | - | m, o |

Soils in the study area are: a: grey or brown calcareous friable clay loams and clays developed on old lacustrine sediments, b: reddish and yellowish sands and loamy sands derived from sediments, granites and acid gneisses, c: reddish friable clays developed on intermediate metamorphic rocks, d: reddish friable sandy clay loams to clays developed on calcareous materials, e: yellowish or reddish sandy clays to clays with moderate organic matter content and high subsoil acidity, f: yellowish or reddish sandy clay loams and sandy clays with low organic matter content, g: reddish or brown sandy loams and sandy clay loams

with high organic matter content, h: undifferentiated very shallow soils, i: coral rag, j: coastal sands, k: grey, brown and reddish loamy sands to sandy clay loams over 'continental deposits', l: bleached sands and loamy sands developed on colluvium of granites and acid gneisses, m: bleached sands and loamy sands with more clayey subsoils developed on sandy sediments, n: dark cracking clays on slopes, o: moderately leached greyish mottled sandy loams to sandy clays, p: dark cracking clays of topographical depressions, q: coarse alluvial sands of river-banks and ridges, r: stratified alluvial fine sands to sandy clay loams of levees and alluvial fans, s: stratified alluvial clays of low floodplain benches and fan swales.

## 3.3 Problem definition

Liebens & Van Molle (2003) emphasise the importance of complete spatial soil databases of high quality as a base for regional SOC mapping and upscaling. However, it is clear that the present soil maps from Mtwara/Lindi are insufficient to serve this goal. An extensive amount of soil data covering southeastern Tanzania is present from different past studies (see paragraph 2.3.1). However, this information is scattered, non-uniform, sometimes interpreted wrongly, incomplete and sometimes the exact location of the profile pits is unknown. The objective of this chapter is to bring together available soil data in a standardised system such as World Reference Base (WRB) (FAO, 2006) and to supply a new soil map of the study area.

## 3.4 Materials & methods

Traditionally soil maps are created involving manual delineation of soil boundaries by field soil scientists. This is an expensive and time-consuming task since many soil sampling points need to be included in the soil survey. In recent years, there has been a significant shift towards digital representation of soil maps and environmental variables that has created the fields of predictive or digital soil mapping (PSM or DSM) (Scull et al., 2003). PSM is the computer-assisted production of digital maps of soil type and soil properties. It involves the creation and population of spatial soil information by the use of field and laboratory observational methods coupled with spatial and non-spatial soil inference systems (McBratney et al., 2002). It applies pedometrics, the use of mathematical and statistical models that combine information from soil observations with information contained in correlated environmental variables and remote sensing images.

This study will make a synergy between the traditional manual method and digital soil mapping. On the one hand, many soil profile descriptions of the study area are already available which makes it possible to create a detailed soil map based on grouping of theses profiles. In total 634 profiles from 4 different datasets (see paragraph 2.3.1) were used as a base for the soil map. In order to maintain objectivity and uniformity, all profiles were re-classified according to the classification key of WRB (FAO, 2006).

On the other hand, several GIS layers with important background information are available and can be used for an accurate delineation of the soil units. The layers which are used include information on geology and topography. Delineations of soil units based on the geology map (Figure 2.3) will be important in the coastal area, where a quick succession of geological deposits is observed. Delineations based on topography (Figure 2.2) will be important at the edges of the plateaus and river valleys. Since the DEM is a continuous elevation map, the process of delineation can be eased by making an automatic classification of topographic units. This was done using the topographic position index (TPI) application

(Jennes, 2006) for Arcview. This extension calculates topographic position index grids from elevation grids, and provides a simple and repeatable method to classify the landscape into slope position (i.e. ridge top, valley bottom, mid-slope etc.) and landform category (steep narrow canyons, gentle valleys, plains, etc.). TPI is naturally very scale-dependent and users should consider carefully what scale is most relevant for the phenomenon being analyzed. Small neighbourhoods capture small and local hills and valleys, while large neighbourhoods capture larger-scale features. Landform category can be determined by classifying the landscape using 2 TPI grids at different scales. The combination of TPI values from different scales suggests various landform types (Figure 3.2).

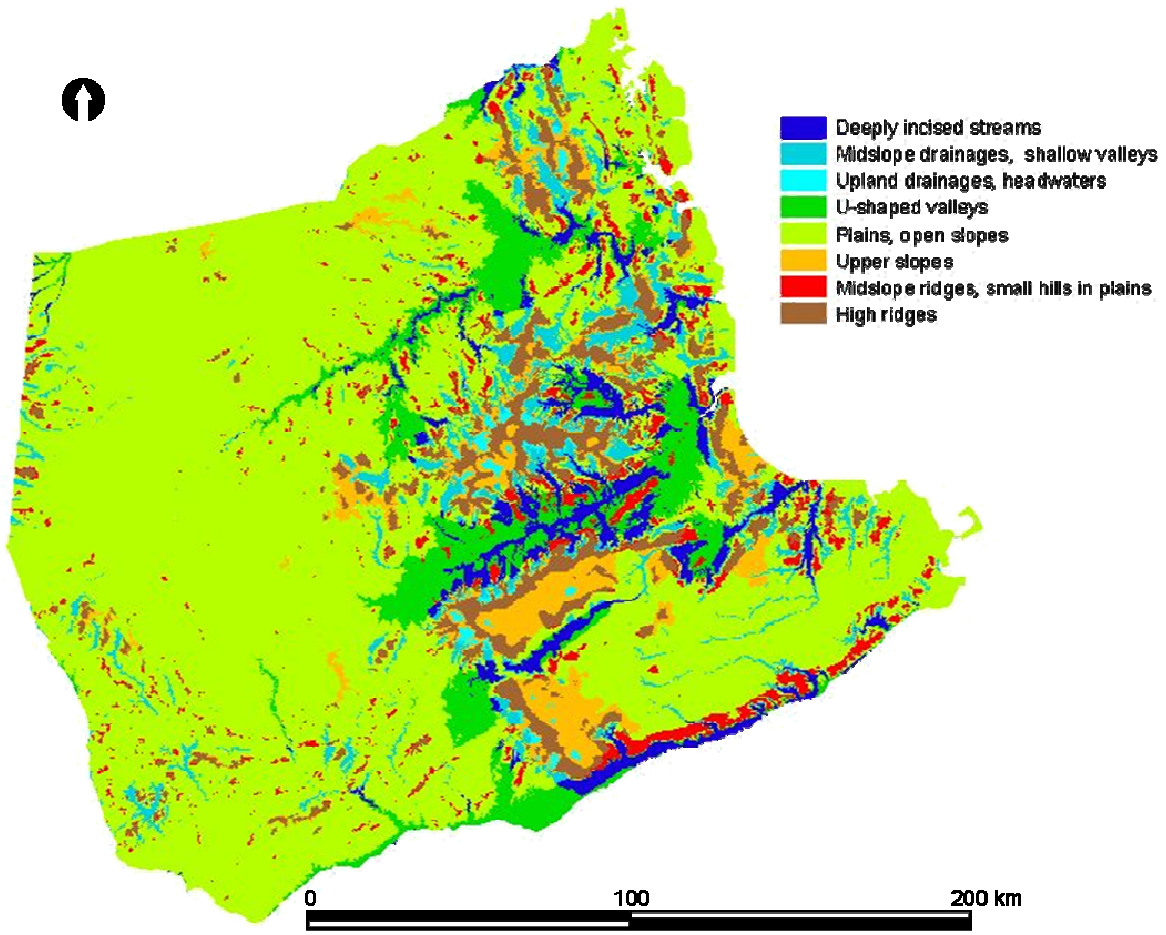



***Figure 3.2 Landform classes of the study area.***

The used methodology based on manual spatial delineation of soil groups with the help of geology and landform units is shown in Figure 3.3. Digitising of the soil map was done in Arcview. Since all soils are found in associations which can not be separately mapped, soil units were defined, with one or two dominant soils (covering more than 50% of the unit) and several associated soils (15-50%) and/or inclusions (< 15%). The relationship between the soil types, geology and landscape will be discussed based on 4 transects running from the SW to the NE of the study area. These transects are chosen as such that they will cross all types of land-units and landscapes. The elevation profile of these transects is drawn based on the DEM using ArcGis.

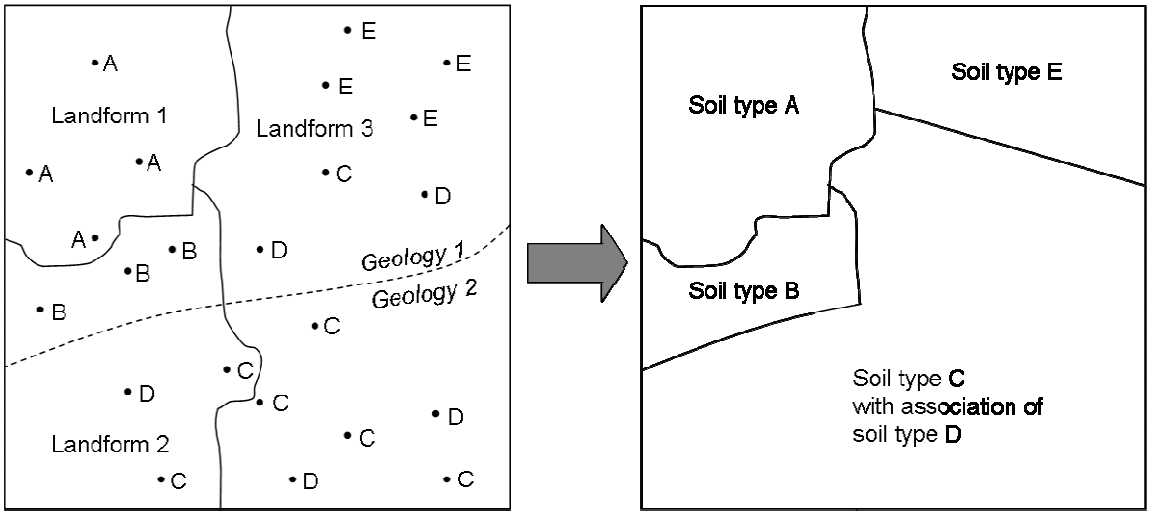



***Figure 3.3 Methodology for soil mapping.***

# 3.5 Results

The new soil map of the study area is presented in Figure 3.4. The dominant, associated and included soils of every soil unit are given in Table 3.1.

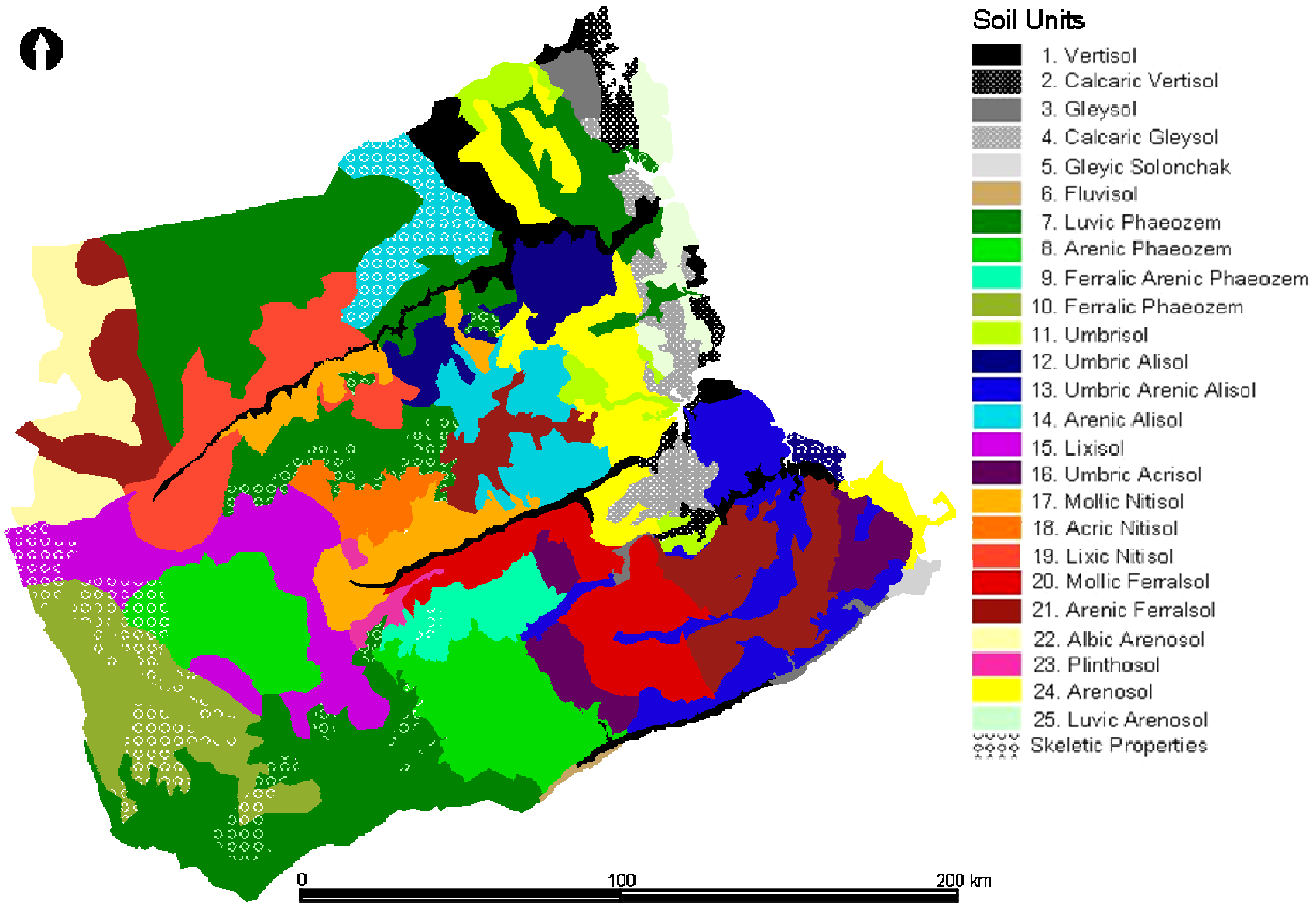



***Figure 3.4 New soil map of the study area.***

***Table 3.2 Overview of the soils units occurring in the new soil map, with their dominant, associated and included soils.***

| Soil unit (No and Name) | | Dominant soils (>50%) | Associated soils (15-50%) | Inclusions (<15%) |
|---|---|---|---|---|
| 1 | Vertisol | Mollic Vertisol (Eutric Pellic Chromic) | Gleyic Mollic Vertisol (Mesotrophic) | - |
| 2 | Calcaric Vertisol | Mollic Vertisol (Calcaric Eutric Pellic) | - | Mollic Gleysol (Calcaric Eutric)<br>Mollic Vertisol (Calcaric Sodic Eutric Pellic) |
| 3 | Gleysol | Mollic Gleysol<br>Umbric Gleysol | - | - |
| 4 | Calcaric Gleysol | Mollic Gleysol (Calcaric Eutric) | Gleyic Mollic Vertisol (Calcaric Eutric Pellic) | Mollic Gleysol (Calcaric Sodic Eutric) |
| 5 | Gleyic Solonchak | Gleyic Solonchak | - | - |
| 6 | Fluvisol | Mollic Fluvisol | - | - |
| 7 | Luvic Phaeozem | Luvic Phaeozem (Pachic Chromic) | Haplic Phaeozem (Pachic Chromic)<br>Luvic Phaeozem (Pachic Skeletic Chromic) | Haplic Luvisol (Chromic)<br>Haplic Alisol (Humic Chromic)<br>Haplic Cambisol (Eutric Chromic)<br>Mollic Stagnosol (Eutric)<br>Mollic Vertisol (Eutric) |
| 8 | Arenic Phaeozem | Haplic Phaeozem (Arenic Chromic) | Haplic Phaeozem (Chromic)<br>Haplic Phaeozem (Skeletic Chromic)<br>Haplic Umbrisol (Arenic) | Haplic Alisol (Arenic Chromic) |
| 9 | Ferralic Arenic Phaeozem | Ferralic Phaeozem (Arenic Chromic) | Haplic Acrisol (Ferric Arenic Chromic) | - |
| 10 | Ferralic Phaeozem | Ferralic Phaeozem (Chromic) | Ferralic Phaeozem (Skeletic Chromic)<br>Haplic Phaeozem (Chromic)<br>Mollic Ferralsol | - |
| 11 | Umbrisol | Haplic Umbrisol (Chromic) | - | - |
| 12 | Umbric Alisol | Umbric Alisol (Chromic) | Haplic Alisol (Chromic) | Haplic Luvisol |
| 13 | Umbric Arenic Alisol | Umbric Alisol (Arenic) | Haplic Umbrisol (Arenic Chromic) | Umbric Alisol (Skeletic Arenic)<br>Ferralic Arenosol (Dystric)<br>Acric Ferralsol (Dystric Arenic Xanthic) |
| 14 | Arenic Alisol | Haplic Alisol (Arenic Chromic) | Haplic Alisol (Skeletic Chromic)<br>Hypoluvic Arenosol (Dystric) | Haplic Lixisol (Arenic Chromic)<br>Haplic Acrisol (Arenic Chromic) |
| 15 | Lixisol | Haplic Lixisol (Chromic) | Haplic Alisol (Chromic) | Haplic Lixisol (Skeletic Chromic)<br>Haplic Cambisol (Dystric)<br>Mollic Gleysol (Eutric) |
| 16 | Umbric Acrisol | Umbric Acrisol (Chromic) | Haplic Acrisol (Arenic Chromic) | Haplic Luvisol (Chromic)<br>HaplicAlisol (Arenic) |
| 17 | Mollic Nitisol | Mollic Nitisol (Eutric Rhodic) | Umbric Nitisol (Rhodic) | Umbric Gleysol (Dystric)<br>Mollic Vertisol (Eutric Chromic) |
| 18 | Acric Nitisol | Ferralic Acric Nitisol (Dystric Rhodic) | Alic Nitisol (Dystric Rhodic) | Stagnic Luvisol |
| 19 | Lixic Nitisol | Ferralic Lixic Nitisol (Eutric) | | Ferralic Acric Nitisol (Dystric)<br>Nitic Alisol |
| 20 | Mollic Ferralsol | Mollic Acric Ferralsol (Dystric Xanthic) | Acric Ferralsol (Dystric Xanthic) | Alisol (Humic Arenic)<br>Haplic Umbrisol (Arenic Chromic)<br>Mollic Vertisol (Ferric Eutric Chromic) |
| 21 | Arenic Ferralsol | Vetic Acric Ferralsol (Dystric Arenic) | Lixic Ferralsol (Eutric Arenic)<br>Haplic Arenosol (Dystric) | Haplic Umbrisol (Arenic)<br>Haplic Alisol (Arenic)<br>Haplic Lixisol (Arenic) |
| 22 | Albic Arenosol | Albic Arenosol (Dystric)<br>Hypoluvic Arenosol (Dystric) | - | - |
| 23 | Plinthosol | Lixic Plinthosol (Eutric Arenic) | Petric Plinthosol (Eutric Arenic)<br>Plinthic Acrisol | - |
| 24 | Arenosol | Haplic Arenosol (Dystric) | Haplic Arenosol (Eutric)<br>Haplic Alisol (Arenic) | Ferralic Arenosol (Dystric) |
| 25 | Luvic Arenosol | - | Hypoluvic Arenosol<br>Haplic Luvisol (Arenic Chromic) | Acric Ferralsol (Dystric Rhodic) |

# 3.6 Discussion

## 3.6.1. Transects

The relationship between the occurring soils, geology and landscape will be discussed based on four transects across the study area (Figure 3.5). The transects show the elevation above sea level against the distance (250 km). Scales of the 2 axes are different, so the vertical evolution is over-exaggerated. Information on the main rivers, towns and geology is added to the drawings, as well as the number of the soil units (see Table 3.2).

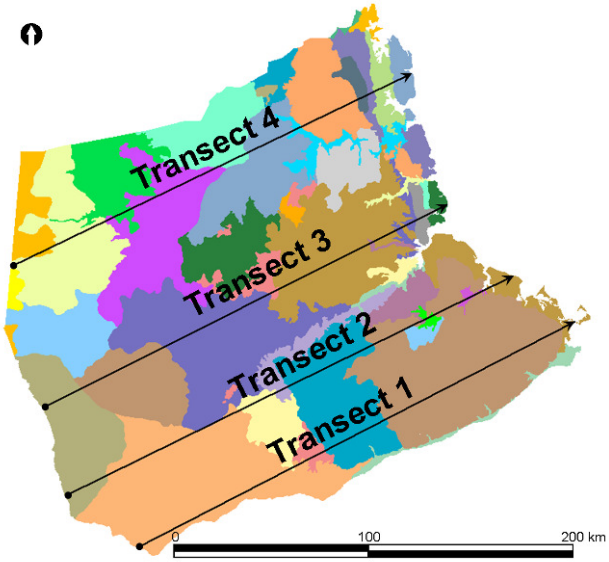



***Figure 3.5 Location of the transects in the study area (overlay on land units map as in Figure 2.4)***

The first transect (Figure 3.6) starts in the utmost southwestern part of the study area, in the **Southern Masasi Plain**. This plain consists of the oldest rocks of the region: the basement rocks (gneisses and quartzites). It forms a more subdued terrain to the north and northwest separated by an arc of inselbergs of the more broken relief to the south. Bennett et al. (1979) describe the pattern of soils as unpredictable and not related to landform nor correlated with vegetation. Soils are generally dark in colour, red rather than brown, with a coarse sandy or loamy sand texture and occasionally increasing clay content with depth. West of Mbangara River deep soils with indistinct horizons are found in broad flat-topped interfluves and in other pockets with a finer textured sandy clay loam (Bennett et al., 1979). De Pauw (1984) found a dominance of reddish and yellowish sands and loamy sands derived from sediments, granites and acid gneisses, with associations of reddish friable clays developed on intermediate metamorphic rocks and reddish or brown sandy loams and sandy clay loams with high organic matter

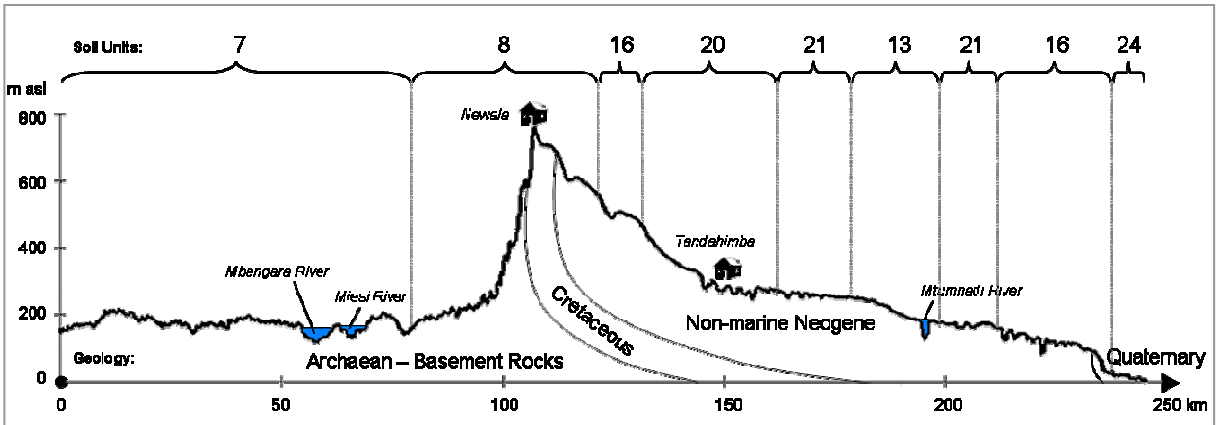



***Figure 3.6 Elevation, geology and soil units of transect 1.***

content. The increasing clay content, high organic matter content of the Ah horizon and yellowish colours classify the dominant soils as Luvic Phaeozems, with associations of Haplic Phaeozems and several inclusions. Skeletic soils occur throughout the plain.

Before reaching Newala the transect passes through very steep **Basement Hills**, which have in many places little or no soils (Bennett et al., 1979). The profiles that were determined were often Skeletic. Newala is situated on the edge of the **Makonde Plateau**. The Makonde Plateau and the Makonde Dissected Plateau are mapped on the geological map as Neogene because of the difficulty of separating Neogene and Lower Cretaceous (Bennett et al., 1979). However, it is thought likely that the higher areas are Cretaceous (Kent et al. 1971). Soils are derived from strongly weathered sandstones, forming weakly structured coarse sandy materials with low levels of nutrients and mineral content and low base saturation, intermixed with pale deep sands, deep dark brown loamy sands over yellowish brow or strong brown sandy loams and occasional sites with sandy clay loam at depth, yellow red (Bennett et al. 1979). De Pauw (1984) describes the same dominant soils as in the Southern Masasi Plain. The influence of the sandy parent material makes all soils Arenic: in the west mainly Arenic Phaeozems occur. On the northern edges of the plateau, Ferralic Arenic Phaeozems are located, while Umbric Acrisols (Chromic and sometimes Arenic) are found on the slopes towards the Dissected Plateau. The **Makonde Dissected Plateau** is capped by silty clays, silts and silty sands with often kaolinitic sandstones (Makonde beds) which are of continental Neogene origin. Soils are deep loamy sands or sandy loams, low in organic material and base saturation. The most common soil type is Acric Arenic Ferralsol with associations of Lixic Ferralsols and Arenosols. In the western higher part of the Dissected Plateau, calcareous material can be found with more fertile topsoils (Bennett et al., 1979). The main soil type here is Mollic Acric Ferralsol. A number of sharply incised rivers cut into the plateau surface, along which there are areas with more finely textured subsoils and a better moisture retention (Bennett et al., 1979): these are mainly Umbric Arenic Alisols with associations of Arenic Umbrisols and in some places Umbric Acrisols. Where the transect reaches the sea it passes through the Msimbati Peninsula. In this area strand lines are visible (Bennett et al., 1979) which are classified as these are Haplic Arenosols.

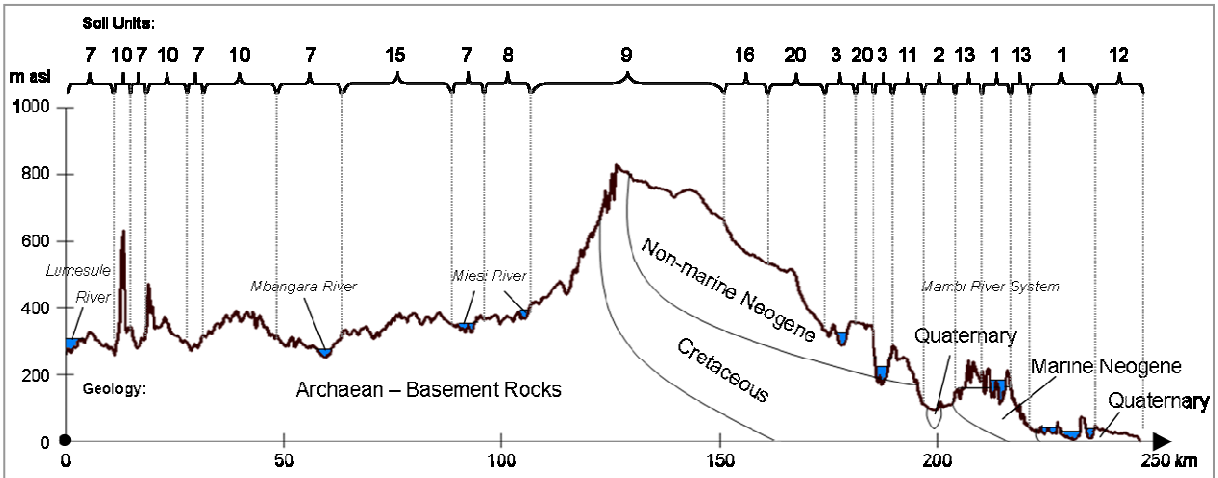



***Figure 3.7 Elevation, geology and soil units of transect 2.***

The second transect (Figure 3.7) starts in the west in the **Inselberg Plain**, which is founded on coarse-grained pegmatitic gneisses. Rising strikingly from this plain are the inselbergs which are chiefly of gneissic

origin and can reach over 800m asl (Bennett et al., 1979). De Pauw (1984) found mainly yellowish or reddish sandy clay loams and sandy clays with low organic matter content, with associated grey brown and reddish loamy sands to sandy clay loams over continental deposits and bleached sands and loamy sands developed on colluvium of granites and acid gneisses. The main soil type is Ferralic Phaeozem, associated with Haplic Phaeozems and Mollic Ferralsols. Most soils are Skeletic. On the lower parts towards the Southern Masasi Plain, some Luvic Phaeozems can still be found. Some Lixisols are found on the outer boundaries of the Nachingwea-Masasi Plain. The Miesi River runs through the **Lulindi Plain**. Geologically this gently sloping plain is composed of gneisses, mostly coarse-grained variations, abundant quartz material and rocks of the crystalline limestone series. Coarse sandy loam to sandy clay loam, dark red to red soils in biotite-hornblende gneiss are intermixed with dark red cracking clays of massive structure, coarse, shallow or stony, reddish brown soils in acid gneiss, and dark grey to black loamy sands to sandy loams in the valleys (Bennett et al., 1979). Soils are consistent with the western part of the Makonde Plateau and are mainly Arenic Phaeozems. On the lower cretaceous arenaceous deposits of the **Makonde Platform** deep well drained coarse-textured soils are formed, which can be compared with the higher parts of the Makonde dissected plateau and which are mainly Mollic Acric Ferralsols with at the edges Ferralic Arenic Phaeozems. The transect passes again several soil units which make up the Makonde Plateau and Makonde Dissected Plateau. Along the Mambi river Mollic and Umbric Gleysols can be observed. After crossing the Mambi River twice, the transect enters the Makonde Embayment and Kitere Plain, and later on also the Mambi Plain. These plains consist of alluvial and lacustrine quaternary material with dark cracking clays (Bennett et al., 1979). De Pauw (1984) found a dominancy of dark cracking clays on slopes, combined with moderately leached greyish mottled sandy loams to sandy clays. The **Kitere Plain** is slightly sodium affected and soils are Mollic Calcaric Vertisols, which are sometimes Sodic. The same soils are found in the local quaternary alluvium of the **Makonde Embayment**. The Embayment has a cretaceous origin with some higher sandstone remnants (Bennett et al., 1979). In the higher parts soils are consistent with the plateau; in the lower parts darker soils are found: Umbrisols. Soils in the **Mambi Plain** and at the delta of the Mambi river are Mollic, sometimes Gleyic, Vertisols. The transect drops to sea level at the **Mtwara Coastal Plain**, which has a marine neogene geology with some quaternary deposits. Limestone is the predominant rock type (Bennett et al., 1979). The soils are deep and well drained: mainly Umbric Alisols and Umbric Arenic Alisols with several associated soils.

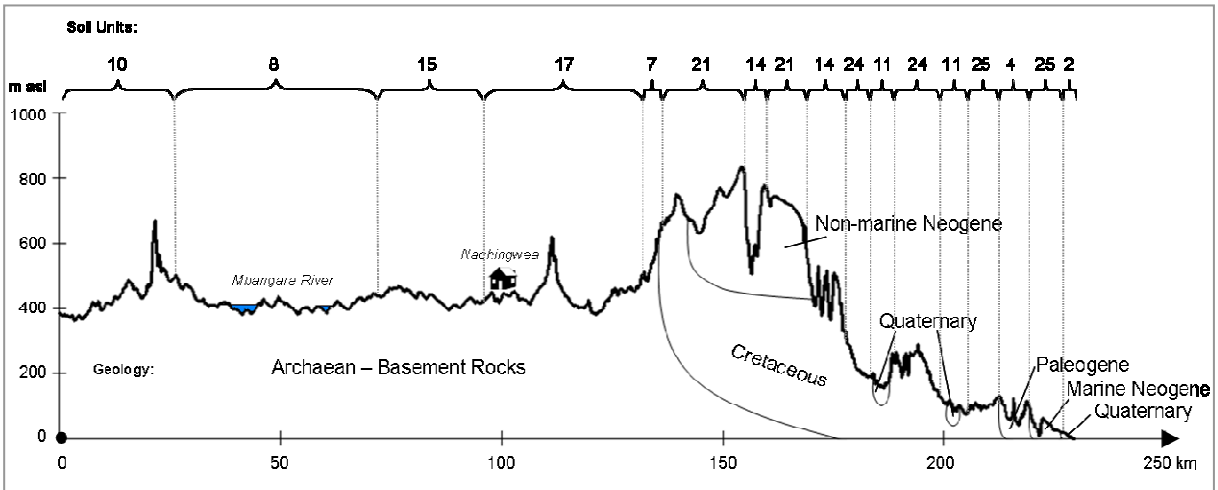



***Figure 3.8 Elevation, geology and soil units of transect 3.***

Transect 3 (Figure 3.8) shows in the western part again the typical peaks of the Inselberg Plain. The Mbangara River runs through a level plain of gneissic origin: the **Upper Mbangara Plain**. Soils are coarsely textured, poorly structured loamy sands over sandy loams with occasional redder profiles and shallow or stony, including gneiss fragments and pedogenic ironstone (Bennett et al., 1979). Although De Pauw (1984) grouped them together with the Inselberg Plain, the coarser parent material makes the soil sandier and classifies them as Arenic Phaeozems. Upon leaving this plain the transect enters another: the **Nachingwea-Masasi Plain**, with Nachingwea located centrally. The main rock types are fine-grained gneisses (in contrast to the more coarse-grained gneisses of the Masasi Series to the south) (Bennett et al., 1979). In the broad flat-topped interfluves in the west soils are consistent with the Lixisols (Chromic) of the Upper Mbwemkuru Plain. The rest of the soils are a uniform deep oxidic red and with indistinct horizons, with a weakly structured sandy loam topsoil over a massive clay subsoil containing a high percentage of free irons: the Nachingwea Red Loam (Bennett et al., 1979). De Pauw (1984) called these soils yellowish or reddish sandy clays to clays with moderate organic matter content and high subsoil acidity. They can be classified as Mollic Nitisols with associations of Umbric Nitisols. In some places of the plain Plinthosols are found, which can be hardened into Petric Plinthosols. At the same longitude as the Makonde Plateau, another plateau system is found, the **Lindi Plateaux and valleys**. The highest part, the Rondo plateau, is continental Neogene. The uniform soils are deep, well drained and coarse-textured with very little horizon differentiation. Clay content increases with depth to sandy loam or sandy clay loam (Bennett et al., 1979). Although De Pauw (1984) makes of them one unit with the Makonde Plateau, soils are somewhat different. On the highest part of the plateau, the main soils are dominantly Acric Arenic Ferralsols with on the surrounding slopes mainly Arenic Alisols. In the more incised terrain towards the east, where the lower Cretaceous deposits reappear, Arenosols occur. Valley bottoms may contain darker, finer textured alluvial soils: Luvic Phaeozems in **Nangaru Valley** and Umbrisols in **Rutamba Valley**. The coastal area is a complex system of different geological deposits and a mixture of soils. **Lindi Plateaux Fringe** is made up of grey/olive clays deposited during the upper Cretaceous by marine transgression (Bennett et al., 1979): the main soil type is a Mollic Calcaric Gleysol. **Lindi Ridge** and **Mchinga Hills** consist of deposits of marine Palaeogene limestone and marl. Main soils are black over olive cracking clays and shallow soils over limestone on steeper slopes (Bennett et al., 1979): mainly Mollic Calcaric Gleysols. The **Coral Shelf** is a marine Neogene formation of coral exposed at the surface. Soils are shallow sandy loams: Hypoluvic Arenosols and Arenic Luvisols. **Lindi** and **Mchinga Coastal Plains** are made of terrestrial Neogene sandstones and limestones with marine Quaternary deposits. Soils are a mixture of coarse-textured well-drained shallow to deep red to pale soils (Bennett et al., 1979): Hypoluvic Arenosols, Arenic Luvisols and Luvic Phaeozems. Parts of quaternary olive grey sodium affected and black soils occur: Calcaric Vertisols, Gleysols and Calcaric Gleysols, which are sometimes Sodic.

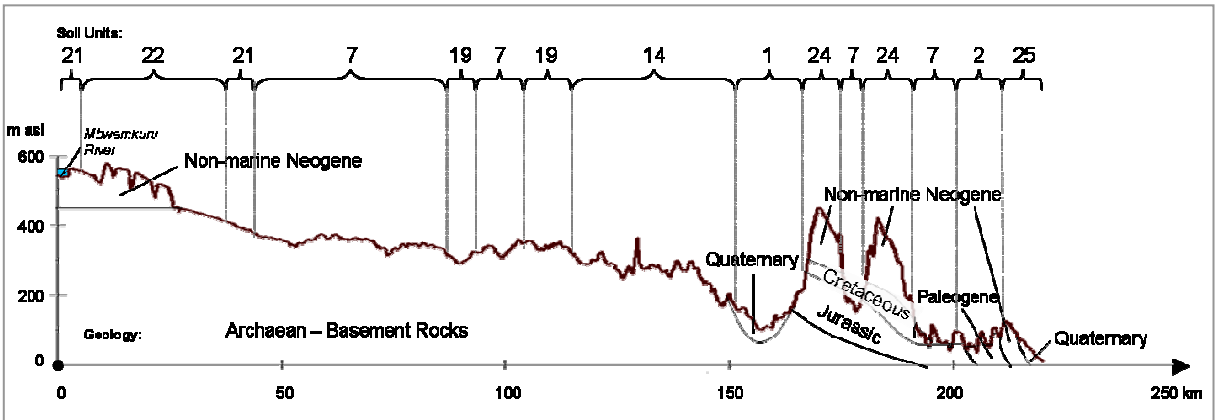



***Figure 3.9 Elevation, geology and soil units of transect 4.***

The last transect (Figure 3.9) starts in the Liwale Plain, which features deep coarse-textured soils on continental neogene sandstone (Bennett et al., 1979). De Pauw (1984) classified these soils as reddish and yellowish sands and loamy sands derived from sediments, granites and acid gneisses; with inclusions of bleached sands and loamy sands with more clayey subsoils developed on sandy sediments, and moderately leached greyish mottled sandy loams to sandy clays. In the new map, these mainly qualify for Albic Arenosols and Hypoluvic Arenosols, with in the wide valleys more finely textured and more poorly drained Acric Arenic Ferralsols. The large level area that makes up the next 50 km of this transect consist of a complex of plains, which is made up of the **Nganga Plain** in the northwest, the **Mid-Mbwemkuru Dissected Plain** in the middle and the **Mnero-Ruangwa** Plain in the southeast. Basement rocks, chiefly gneisses and quartzites, are present in all plains. De Pauw (1984) found mainly reddish friable clays developed on intermediate metamorphic rocks in the lower parts and grey, brown and reddish loamy sands to sandy clay loams over continental deposits in the more sloping areas. Bennett et al. (1979) observed the same trend with deep well drained red clay soils with high base saturations occurring along a NNE trend in the Mbwemkuru River valley: the most common soil type is Ferralic Acric Nitisol and close to the river a more fertile Mollic Nitisol. In the valley bottoms imperfectly drained dark yellowish clay loams or black clays with surface cracking occur (Bennett et al, 1979): these are Vertisols. On the slopes and in the isolated hills of the Mnero-Ruangwa Plain erosion leads to a loamy sand or sandy loam texture with sometimes shallow or stony soils. Most soils here are Luvic Skeletic Phaeozems. The altitude drops slightly for the next 50 km, when the transect crosses the **Lower Mbwemkuru Dissected Plain**, which makes together with the **Matandu Mavuji Plain** another large complex situated on basement rocks. These rocks are of predominantly gneissic composition with some quartzites (Bennett et al., 1979). There is a complex pattern of basement soils which were classified by De Pauw (1984) as dominantly yellowish or reddish sandy clay loams and sandy clays with low organic matter content and in the new map as Luvic Phaeozems with on the slopes shallow or stony Arenic Skeletic Alisols. In the fertile plain south of the Mbwemkuru river (south of the transect) a large complex of Umbric Alisols is present. In the **Mbwemkuru Alluvial Plain** the transect crosses an area of Vertisols. **The Kilwa Uplands** are cretaceous with continental neogene higher plateaus, sandstone at the surface and limestone in substrata exposed in escarpments (Bennett et al., 1979). In the higher areas deep sandstone soils with red sandy clay loam subsoils are found: these are Arenosols and a few Ferralic Arenosols. On the slopes and in the **Mandawa-Mahokonde Anticline** Luvic Phaeozems are found and in the lower areas towards the Mavuji River (north of the transect) soils are heavier with paler colours and often impeded drainage (Umbrisols).

The geology and soil complex found in the coastal area is comparable to transect 3. (Calcaric) Gleysols occur in the marine Cretaceous material of the **Kilwa Dissected Plain** (north of the transect). Marine Paleogene limestone and marl, with outliers of neogene material, appear in the **Kiswere Dissected Zone**, forming Calcaric Vertisols. **Pande Coastal Plain** is made up from terrestrial neogene sandstones and limestones with marine quaternary deposits. The main soils are Hypoluvic Arenosols and Arenic Luvisols.

## 3.6.2. Comparison with the old soil map

Until now the most commonly used soil map of Southeast Tanzania was that of the ITCRP (1981). However, after re-evaluating the soil databases and reclassifying the soil units according to WRB (FAO, 2006), it has been established that the ITCRP map shows several inaccuracies , which are summarised in Table 3.3.

***Table 3.3 Soil units that are different between the soil classification in the Italian soil map (ITCRP, 1981) and the soil units of the new soil map.***

| Land unit | Soil Units Italian map (ITCRP, 1981) Classification: FAO-UNESCO (1974) | Main Soil Units of new map Classification: WRB-FAO (2006) |
|---|---|---|
| **Mtwara Coastal Plain** | Orthic Luvisol | Umbric Arenic Alisol |
| **Makonde Dissected Plateau** | Cambic Arenosol | Arenic Ferralsol<br>Mollic Ferralsol |
| | Orthic Luvisol | Umbric Arenic Alisol |
| **Makonde Plateau** | Cambic Arenosol | Arenic Phaeozem<br>Ferralic Arenic Phaeozem<br>Umbric Acrisol |
| **Southern Masai Plain** | Chromic Cambisol | Luvic Phaeozem |
| **Inselberg Plain** | Cambic Arenosol | Ferralic Phaeozem |
| **Upper Mbwemkuru Plain** | Cambic Arenosol | Lixisol |
| **Liwale Plain** | Cambic Arenosol | Albic Arenosol<br>Arenic Ferralsol |
| **Nganga Plain** | Eutric Gleysol | Luvic Phaeozem |
| **Mid-Mbwemkuru Dissected Plain** | Ferric Luvisol | Lixic & Mollic Nitisol<br>Luvic Phaeozem |
| **Nachingwea Masasi Plain** | Ferric Luvisol | Acric & Mollic Nitisol<br>Luvic Phaeozem |
| **Matandu Mavuji Plain** | Chromic Cambisol | Arenic Alisol<br>Luvic Phaeozem |
| **Lower Mbwemkuru Dissected Plain & Mnero Ruangwa Plain** | Chromic Cambisol | Luvic Phaeozem<br>Umbric Alisol |
| **Lindi Plateaux & Valleys** | Cambic Arensol<br>Orthic Ferralsol | Arenic Ferralsol<br>Arenic Alisol |

### River valleys

Along the main rivers Fluvisols, Gleysols and Vertisols are found on both maps. On the new map, areas of Umbrisols and Phaeozems were observed in the river valleys, but on a small scale, which could not be recognised in the ITCRP map.

### Coastal area

In the Mtwara Coastal Plain and in the valleys and lower parts of the Makonde Dissected Plateau deep soils with an argic horizon and a high CEC were seen. With the FAO-UNESCO (1974) classification of the ITCRP map they were defined as Luvisols, but a tendency of low base saturations in the soil descriptions made a classification as Alisols preferable, a soil unit that was only introduced later.
The Lindi and Kilwa coastal areas consist of a mixture of Arenosols (mainly at the coastline), Vertisols and Gleysols. The two maps show the same trend, although the new map is more detailed.

### Plateaus

On the ITCRP map the whole Makonde Platform, Makonde Plateau and the higher parts of the Makonde Dissected Plateau are mapped as Cambic Arenosols: these are loamy sand or coarser soils and in the FAO-UNESCO (1974) this property is given high priority. In the new classification system of WRB (FAO, 2006) other soil properties are given priority in classification: the low CEC of a large part of the profiles classifies the higher part of the Dissected Plateau and the Makonde Platform as Arenic or Mollic Ferralsols. On the elevated Makonde Plateau, where lower temperatures impede decomposition of organic matter, Mollic A-horizons are found, leading to a classification as Ferralic Arenic Phaeozem.
On the highest part of the Lindi Plateau, Cambic Arenosols and Orthic Ferralsols are seen on the ITCRP map. It has been remapped as a large zone of Arenic Ferralsols surrounded by Arenic Alisols. On the eastern outliers of the plateau Arenosols are defined on both maps.

### Plains

The Chromic Cambisols which are found in the Lulindi Plain and the Southern Masasi Plain of the ITCRP map are indeed yellowish to red deep soils with little profile development. However the Mollic A-horizon again qualifies the soils as Chromic Phaeozems, which are sandy on the transition with the plateau (Arenic) and have an argic horizon in the Southern Masasi Plain (Luvic). On the ITCRP map, a large zone of Cambic Arenosols stretches from the Inselberg Plain, over the Upper Mbwemkuru Plain to the Liwale Plain. Yet only in the Liwale Plain soils have a loamy sand or coarser texture due to the Neogene Sandstone of the higher parts. Soils on this sandstone are light-coloured (Albic). In the lower parts in the Basement area, soils still contain a high percentage of sand but have a low CEC and therefore are classified in the WRB-system (FAO, 2006) as Arenic Ferralsols. Soils in the Inselberg and Upper Mbwemkuru Plain are not sandy and are wrongly classified as Arenosols. They are connected to the other fertile soils with low CEC in the southern plains: Ferralic Phaeozems in the Inselberg Plain and a mixture of soils summarised as Lixisols in the Upper Mbwemkuru Plain. More eastward a band of plains is defined by the ITCRP as Ferric Luvisols. These soils are defined by Bennett et al. (1979) as the Nachingwea Red Loam: uniform deep oxidic red profiles, low in organic matter and with indistinct horizons, with a weakly structured sandy loam topsoil over a massive clay subsoil containing a high percentage of free irons. In the present classification system, these types of soil are defined as Nitisols. On the higher parts fertile soils

with an argic horizon are formed: the sudden clay increase prohibits a classification as Nitisol: these soils are Luvic Phaeozems. According to the ITCRP map, soils of the Matandu Mavuji Plain, Lower Mbwemkuru Dissected Plain, Mnero Ruangwa Plain and parts of the Kilwa Uplands are consistent with the soils in the southern plains and are defined as Chromic Cambisols. Indeed these profiles show many similarities with the soils in the south and are again defined as Luvic Phaeozems (Chromic). Only the shallow soils on the basement rocks classify as Skeletic Alisols.

It can be concluded that the ITCRP soil map can not be used as a reliable base for a this SOC study. It was originally made in the scope of a cashew production research programme, focussing on the main large landscape units. Large forested areas which could not be used for cashew production were not examined. Differences in soil groups can be attributed partly to changes in the classification system: new classes were added and the priority of classification of reference soil groups changed. On the other hand, some soil groups such as Nitisols or Phaeozems were just wrongly classified in the ITCRP soil map.

### 3.6.3. Implications for the SOC stock

From the new soil map, some implications and expectations related to the SOC stocks can be formulated. Although the largest area of the study area is situated on very old Precambrian deposits with low cation exchange capacities and with dry and warm conditions, their organic carbon content in the A-horizon is high (>0,6%): the largest part of these plains is classified as Phaeozem. It is expected that carbon concentrations in the underlying horizons remain relatively high in the finer textures of the Luvic Phaeozems and drop to low levels in the coarser Arenic Phaeozems. The central area of Nitisols is generally not much appreciated by the farmers because of the difficulty working these heavy clays (Bennett et al., 1979), but their potential for carbon sequestration is expected to be high. Vertisols are found along rivers and in the coastal area and are expected to have the highest carbon stocks. Where strongly weathered Cretaceous sandstones occur, soils qualify as Arenosols and Ferralic Arenosols. Soil organic carbon levels in these soils are expected to be low.
A quantitative analysis of SOC stocks will be dealt with further in this thesis.

## 3.7 Conclusions

A new soil map based on 280 full profile descriptions and analyses and 354 physical profile descriptions was created. The two most important soil-forming factors were parent material and topography. For example, coarse sandy soils on Cretaceous material can be easily distinguished from sandy loams or sandy clay loams on Archean basement rocks. Differences were observed between fertile river valleys, plains with little profile development, slopes with clay illuviation and weathered plateaus. The soil and landscape descriptions made by Bennett et al. (1979) and De Pauw (1984) offered a sound baseline for establishing the revised soil map of southeastern Tanzania. The only available FAO/Unesco (1974) soil map, made by the ITCRP (1981), revealed many inaccuracies and is not recommended for further use. Large areas of the study areas could be of interest for soil organic carbon sequestration.

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# 4 Land Use and Land Use Change

# 4.1 Introduction

People have reshaped the earth continually but the present magnitude and rate of change are unprecedented. These changes encompass the greatest environmental concerns of human populations today, including climate change, biodiversity loss and the pollution of water, soils and air. Nowadays it is realized that it is very important to know how land cover has changed over time, in order to assess the changes one could expect in the (near) future and the impact these changes will have on peoples' lives (Di Gregorio & Jansen, 1998). Land use change is an important determinant of the human-induced imbalance of the global C cycle (see Figure 1.1) and the estimation of the magnitude of this change is therefore important in the calculation of regional C budgets. The scope of this chapter is to develop a recent land use map and to calculate the size of the land use changes that have occurred.

# 4.2 Definitions

Land use and land cover are distinct concepts although the two terms are often used interchangeably. Land cover includes a (bio)physical description of the earth's surface. It is that which overlays or currently covers the ground (FAO, 2009). When considering land cover in a very pure and strict sense it should be confined to describe vegetation and man-made features. Consequently, areas where the surface consists in bare rock or bare soil should be described as land itself rather than land cover. In addition, it is disputable whether water surfaces are a real land cover. However, in practice, the scientific community usually describes those aspects under the term land cover (Di Gregorio & Jansen, 1998) and the basic categories include vegetation (trees, bushes, fields, lawns), bare soil, hard surfaces (rocks, buildings) and wet areas and bodies of water (watercourses, wetlands) (EC, 2000).

Land use is characterized by the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it (FAO, 2009). Definitions of land use in this way establish a direct link between land cover and the actions of people in their environment. For example, "grassland" is a cover term, while "rangeland" or "tennis court" refers to the use of a grass cover (Di Gregorio & Jansen, 1998). Land-use and land-cover change (LULCC or LUCC) are general terms for the human modification of Earth's terrestrial surface.

Many authors have done classification of land use and land cover using different general or sectoral classification systems (Young, 1994). Surveys of land cover are largely based on data from remote sensing, with control by field observation. Mapping is normally carried out inductively, that is, by commencing with the classes that can be distinguished in the surveyed area (visually or by data processing) and constructing a map legend from these. Such legends are based on classes of land cover, mapped individually where possible, otherwise in spatial combinations where necessary. Land cover types are extremely varied, and it will continue to be necessary to include classes of local significance. However, in order to obtain harmonization and standardization, FAO developed a comprehensive, standardized and a priori land cover classification system (LCCS) that is designed to meet specific user requirements, and created for mapping exercises, independent of the scale or means used to map (Di Gregorio & Jansen, 1998). A universally accepted land use classification system has not yet been developed (Young, 1994).

In the context of this thesis, a land use classification seems the most appropriate. For example in the scope of SOC measurements, natural crops and herbaceous vegetation or tree crops and woodlands have to be distinguished.

# 4.3 Land use in Tanzania

No recent numbers are available on land use distribution or land use change in southeastern Tanzania. A first impression will however be given by looking at data at country scale.

## 4.3.1. Land use distribution

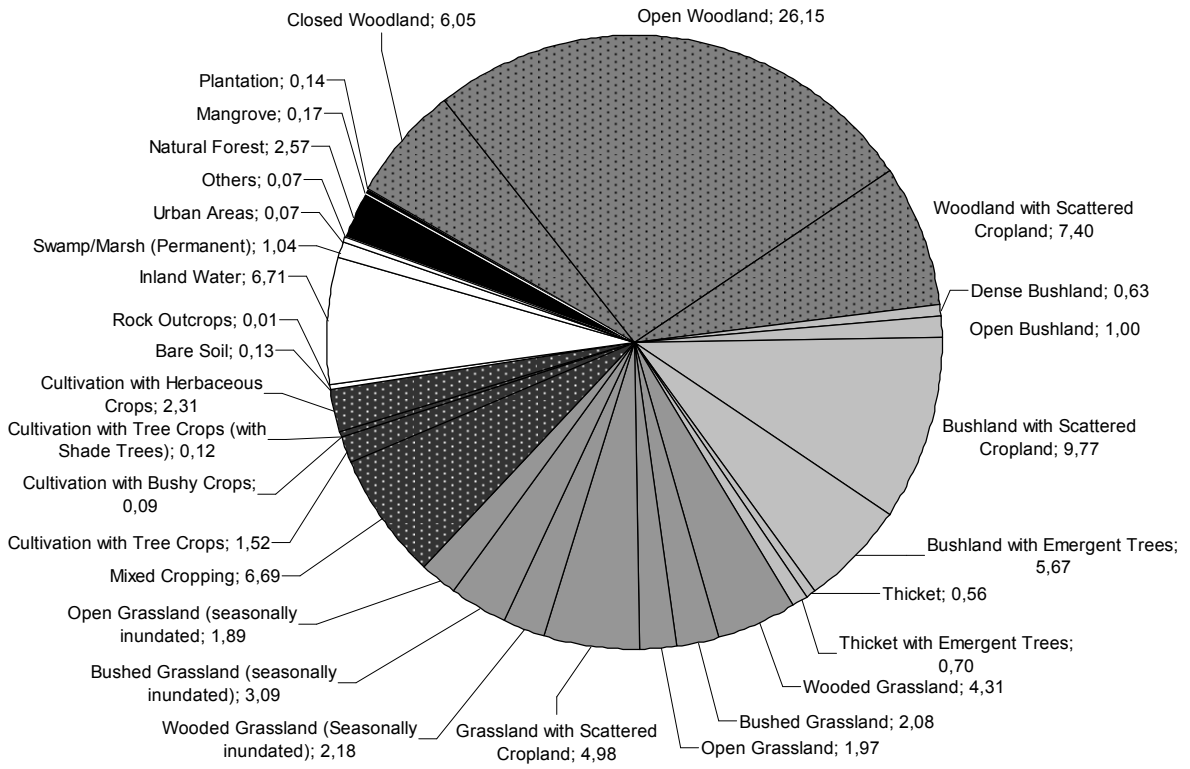



***Figure 4.1 Land use distribution of Tanzania. Numbers represent the percentage of land covered by that class (based on data from MNRT, 1996).***

The average distribution of land use in Tanzania is presented in Figure 4.1. The major land use is woodland, with 40%. Grassland (20%) and bushland (18%) are also important land uses, while cultivation (11%) and forest (3%) are only of minor importance.

## 4.3.2. Land use change

An idea of the land use change in the study area is obtained by comparing land use in Tanzania between 1947 and 1990 (Table 4.1). It is clear that the main changes in land use/land cover are at the expense of the forest cover in order to establish cultivated land.

***Table 4.1 Vegetation distribution and changes during 1947-1990 (kha) (CEEST, 1994).***

| | Year | | | |
|---|---|---|---|---|
| Vegetation Class Types | 1947 | 1956 | 1976 | 1990 |
| **Tropical Closed Forests** | 7727 | 1885 | 1455 | 1100 |
| **Mangrove Forests** | 93 | 80 | 80 | 80 |
| **Miombo Woodlands** | 35392 | 38706 | 26702 | 25616 |
| **Wooded Grasslands (Savanna)** | 19746 | 20037 | 14205 | 16662 |
| **Bushlands/Thickets** | 9481 | 10551 | 9878 | 7464 |
| **Thickets** | 772 | 569 | 727 | 784 |
| **Grasslands** | 6049 | 4011 | 4770 | 6295 |
| **Desert/Semi Desert** | 867 | 460 | 491 | 163 |
| **Cultivated/Abandoned Lands/Settlements** | 8407 | 12227 | 28481 | 28215 |
| **Swamps, Bogs and Water Bodies** | 5975 | 5983 | 7720 | 8130 |
| **Total** | 94509 | 94509 | 94509 | 94509 |

During the period of 1976 to 1990, 24.4 % of original tropical closed forest cover was transferred to other classes as follows:

- 115 kha were converted to permanent agricultural land and pasture. This was more likely a result of population pressure rather than planned land-use change.
- 38 kha were converted to secondary forest; that is thickets (8kha) and bushland/thickets (30 kha).
- 202 kha converted to wooded grassland or fragmented forest, which in turn changed to other land cover as an intermediate stage towards permanent agriculture and pasture (CEEST, 1994).

Estimations of the deforestation rate in Tanzania range between 300,000 and 600,000 ha $yr^{-1}$ in the 1980s (Makundi & Okiting'ati, 1995). Given the fact that the rate has been increasing over the period, this estimate would tend to support a thesis of a high estimate during 1990 (CEEST, 1999).

The rate at which the forest area is being converted to other land-uses has been increasing with the rapid increase in population, which is mainly land-dependent (Sathaye et al., 1995). Forestland is converted to agricultural land as well as depleted for production of woodfuel, especially charcoal. Other factors that contribute to deforestation and degradation include logging, overgrazing and forest fires (CEEST, 1999). Land degradation has been a result of among other things, insecure land tenure resulting from absence of land use planning (Dallu, 2003).

# 4.4 Land use in the study area

## 4.4.1. Land use systems

Several authors have stated that the original vegetation of southeastern Tanzania consists of forest or forest-woodlands (Bennett et al., 1979a; Clarke & Robertson, 2000; Burgess et al., 2005). In some places these original vegetation types still remain. Due to human influence, this natural vegetation has been replaced largely by secondary vegetation and agriculture.

### *4.4.1.1. Natural vegetation*

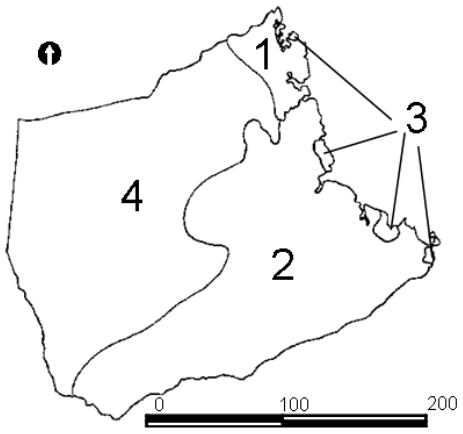



***Figure 4.2 Eco-regions in the study area: (1) Northern and (2) Southern Zanzibar-Imhambane coastal forest mosaic, (3) East African mangroves and (4) Eastern Miombo woodlands (NGS & WWF, 2009).***

According to the NGS & WWF (2009), 4 eco-regions are found in the study area (Figure 4.2). An eco-region is hereby defined as a geographically distinct area of land or water that is characterized by climate, ecological features, and plant and animal communities. 2 ecotypes belong to the Tropical and Subtropical Moist Broadleaf Forest: the Northern and Southern Zanzibar-Imhambane coastal forest mosaic. Along the coastline and in river deltas mangroves are found, belonging to the eco-region of the East African mangroves. The eco-region of the large plains is called the Eastern Miombo woodlands, belonging to the Tropical and Subtropical Grasslands, Savannas and Shrublands (NGS & WWF, 2009).

The Northern Zanzibar-Inhambane coastal forest mosaic runs along the coast from central Somalia to the Lukuledi river in Tanzania. From here, the Southern forest mosaic extends down to nearly the mouth of the Limpopo river (Mozambique). Since it falls under the influence of the Madagascar rain shadow, it receives typically lower rainfall than the northern part. In terms of the physogeographical classification of Moll and White (1978) and White (1983) both eco-regions form a part of White's Zanzibar-Inhambane regional mosaic. Coastal forests are considered remnants of the original pre-Miocene Pan-African Lowland Forest, the vegetation climax for this eco-region (Clarke & Robertson, 2000). Chlorophora excelsa (Welw.) Benth. (better known as Iroko) is a major forest species which can also be found as a forest relict on cultivated ground. The current vegetation consists of a mosaic of dry forests, savanna woodland, thickets, swamps and littoral vegetation types (NGS & WWF, 2009).

Overall, there are more than 4500 plant species and 1050 plant genera, with around 3000 species and 750 genera occurring in forest. At least 400 plant species are endemic to the forest patches and approximately another 500 are endemic to the intervening habitats that make up 99 percent of the eco-region area (NGS & WWF, 2009). It is considered the hotspot most likely to suffer the most plant and vertebrate extinction for a given loss of habitat (Brooks et al., 2002). Because of the small area of the hotspot, the densities of these endemics are among the highest in the world. The highest biodiversity is found in the various kinds of closed canopy forest vegetation although this makes up only 1 percent of the total area of the coastal

forest mosaic. A substantial proportion of the endemic plants are confined to a single forest (for example rondo forest has 60 strict endemics) (Clarke et al., 2000).

Over thousands of years, the forests in this eco-region have been reduced dramatically. The most important threats to coastal forests in Tanzania are agriculture and encroachment, timber extraction, pole-wood cutting and fire, leading to degradation, fragmentation and loss of the only remaining habitat for many known (and unknown) globally threatened species (Burgess et al., 2005). In Tanzania forested areas are not larger than 40 km2, and typically are much smaller (Burgess et al. 1996; Burgess & Clarke, 2000). Despite the high biological importance, legal protection of important areas in the hotspot is either weak, lacking altogether or poorly enforced. Most sites lack strategic management and action plans. On the positive side, these problems are widely recognized and various initiatives (including institutional, policy and legislative reforms) have been launched to address them (Burgess et al., 2005).

Several authors state that the natural vegetation of this area would be a form of closed-canopy forest and that under prevailing climatic conditions nothing is likely to prevent development of vegetation to forest except for poor soil conditions and/or periodic man-made disturbance (Bennett et al., 1979a; Burgess et al., 2005).

At the coastline the littoral vegetation transitions into mangrove vegetation, especially in sheltered bays and along rivers. As highly productive nurseries for fish and prawns, eastern African mangroves significantly enhance the biodiversity of surrounding marine habitats while providing vital habitat for migratory birds, marine turtles, dugongs and porpoises. The Rufiji Delta system is one of the largest stands of mangrove on the East African coast. However, Eastern African mangroves are threatened in many areas by overuse and conversion by a growing human population that utilizes the mangroves for rice farming, shrimp aquaculture, and for construction materials and the timber trade (NGS & WWF, 2009). Common species found in the study area include *Rhizophora* sp., *Avicennia* sp. and *Lumnitzera racemosa* Willd. Dense associations of the bushy sub-succulent *Sueda monoica* Forsk. Ex. J.F. Gmel. and the grass *Paspalum vaginatum* Sw. often occur on the landward side of the mangroves (Bennett et al., 1979a).

Confined to the lower elevations of the Central African Plateau, the Eastern Miombo Woodland eco-region ranges from southern Tanzania to northern Mozambique and Malawi. Only low-nutrient vegetation grows in the dry climate and poor soil. Miombo woodlands form the dense forest woodland that bisects Africa directly south of the Congo Basin and East African savannas. It stretches all the way from Angola in the west to Tanzania in the east (NGS & WWF, 2009). Rodgers (1982) estimated that half of Tanzania consists of miombo woodland and that it constitutes the single largest vegetation type in East Africa. It is a fire-dependent para-climax vegetation characterized by an open canopy, a shrub layer which varies in density, percentage cover and species composition (Rodgers, 1982) and a dense grass layer (Burgess & Clarke, 2000). These woodlands are dominated by trees of the subfamily *Caesalpinioideae*, particularly species belonging to the *Brachystegia*, *Julbernardia* and *Isoberlinia* genera, which seldom appear outside miombo (Campbell et al., 1996). Much of the area covered by this eco-region overlaps with White's (1983) floristically impoverished drier Zambezian miombo woodland. Deciduous riparian forest lines the numerous rivers in the area, while dry forest and thicket associations are also found in the eco-region, especially in rocky places. Fire is an important ecological factor in miombo woodland. The strong

seasonality in precipitation leaves the vegetation dry for several months of the year, and thunderstorms at the start of the rainy season can easily set the vegetation alight (Werger & Coetzee, 1978). However, in addition to being naturally fire-prone, miombo is frequently burned by people to clear land for cultivation, to maintain pastures for livestock, or to drive game animals to positions where they can be easily hunted. Other threats are selective felling of African blackwood or Mpingo (*Dalbergia malanoxylon* Guill. & Perr) for the production of tourist-trade carvings and deforestation for cultivation (NGS & WWF, 2009).
Woodland species found in the study area by Bennett et al. (1979a) include *Brachystegia microphylla* Harms, *Pteleopsis myrtifolia* (M.A. Lawson) Engl. & Diels, *Albizia forbesii* Benth., *Ozoroa insignis* Delile, *Xeroderris stuhlmannii* (Taubert) Mendonca & Sousa, *Sclerocarya* sp., *Markhamia* sp, *Xeroderris stuhlmannii* (Taubert) Mendonca & Sousa, *Trachylobium verrucosum* (Gaertn.) Oliv., *Afzelia quanzensis* Welw., *Brachystegia spiciformis* Benth., *Cordyla africana* Lour., *Pterocarpus angolensis* D.C., *Berlinia orientalis* Brenan, *Baphia macrocalyx* Harms and *Xylopia odoratissima* Welw. ex Oliv..

#### 4.4.1.2. Secondary vegetation

Secondary forests are defined as forests regenerating largely through natural processes after significant human and/or natural disturbance of the original forest vegetation at a single point in time or over an extended period, and displaying a major difference in forest structure and/or canopy species composition with respect to nearby primary forests on similar sites (Chokkalingam & De Jong, 2001). Bennett et al. (1979a) describe different forms of bushland, thicket and woodland thicket, which are low, dense and inpenetratable types of bush lacking a grassy ground cover including low shrubs or trees as well as emergent trees of moderate height, often based on termitaria. Complex vegetation mixtures of vegetation types in various stages of secondary development are described by Bennett et al. (1979a) as woodland-bushland-thicket-wooded grassland complex and woodland-bushland-wooded grassland complex. Both are the result of a long history of disturbance, the first type due to cultivation and the second due to extreme seasonal fluctuations in soil moisture content.
Typical thicket species are *Lonchocarpus* sp., *Dichapetalum* sp., *Dichrostachys cinerea* (L.) Wight & Arn., *Diplorhynchus condylocarpon* (Müll.Arg.) Pichon, *Grewia* sp., *Capparis* sp., *Dienbollia* sp., *Olax pentandra* Sleumer, *Olax* sp., *Commiphora serrata* Engl., *Commiphora africana* (A.Rich.) Engl., *Salacia stuhlmanniana* Loes., *Securinega virosa* (Roxb. ex Willd.) Baill., *Strychnos* sp., *Dombeya* sp., *Uvaria* sp. and the vines *Entada* sp., *Landophia* sp. and *Combretum* sp. (Bennett et al., 1979a).

#### 4.4.1.3. Agriculture

Farming system: the general farming system in Mtwara and Lindi regions is one of manual peasant agriculture with very few cash inputs, producing for subsistence and a sizeable cash surplus. The main starchy staples are sorghum (*Sorghum bicolor* (L.) Moench), cassava (*Manihot esculenta* Crantz), maize (*Zea mays* L.) and rice (*Oryza sativa* L.). Pigeon pea (*Cajanus cajan* (L.) Millsp.) and cowpea (*Vigna unguiculata* (L.) Walp.) are the main legumes. Peanut (*Arachis nypogaea* L.), bambara nut (*Vigna subterranean* (L.) Verdc.). Hyacinth bean ('lablab' or 'fiwi') (*Lablab purpureus* (L.) Sweet) and mung bean ('gram') (*Vigna radiate* (L.) R. Wilczek) are food legumes of less importance (Bennett et al., 1979b).

Cashew (*Anacardium occidentale* L.) is very widely grown and is by far the most important cash crop. Trees are widely spaced and can grow in good conditions up to a height of 20m (Behrens, 1996). Weeds are considered a major problem because they conceal fallen nuts and constitute a fire hazard, so intensive weeding is common practice (Ngatunga, 2001).

Sesame (*Sesamum indicum* L.) is also widespread and is next in importance as a cash crop, followed by the food crops. Coconuts (*Cocos nucifera* L.) are important near the coast. Oranges (*Citrus sinensis* (L.) Osbeck) are an important cash crop in some areas (Bennett et al., 1979b). Minor crops include pearl (*Pennisetum glaucum* (L.)R.Br.) and finger millet (*Eleusine coracan* L.), tomato (*Solanum lycopersicum* L.), okra (*Abelmoschus esculentus* (L.) Moench), onion (*Allium cepa* L.), amaranth (*Amaranthus* L.), sweet potato (*Ipomoea batatas* (L.) Lam.), pumpkin and squash (*Cucurbita* sp.), cucumber (*Cucumis sativus* L.), watermelon (*Citrullus lanatus* (Thunb.) Matsum. & Nakai), banana (*Musa* sp.), mango (*Mangifera indica* L.), papaya (*Carica papaya* L.), citrus fruit (*Citrus* sp.), soya bean (*Glycine max* (L.) Merr.), castor oil plant (*Ricinus communis* L.), sunflower (*Helianthus annuus* L.), yam (*Dioscorea balcanica* Kosanin) and eggplant (*Solanum melongena* L.). Tobacco (*Nicotiana tabacum* L.) has been introduced in some places (Bennett et al., 1979b).

The mixture of starchy staples helps to provide a regular food supply and reduce storage periods and losses. The two principal starchy staple food crops in the two regions are sorghum and cassava. Both crops are drought-resistant and capable of reasonable yields on soils of fairly low nutrient status, but cassava is the most tolerant of low fertility. Consequently very poor, continuously cropped soils support a high population cassava dominates the annual cropping system. Where population density is lower, bush fallowing is possible and this allows some restoration of fertility. In these areas cultivation of sorghum on a large scale becomes more practicable. Maize and rice have higher water and nutrient requirements (Bennett et al., 1979b).
Mixed intercropping, that is the growing of two or more crops simultaneously with no distinct row arrangement, is the predominant system employed by farmers in this region. The only annual crop, which is commonly grown in pure stands, is wet-land rice, though sole cropping is often practiced for some of the legumes, sesame, sorghum and maize. Most of the mixtures are fairly complex; containing up to 8 crops, but there are usually one or two crops dominant in each (Bennett et al., 1979b). In many areas a two-tier intercropping system is practiced as a result of the widespread cultivation of cashew. Cashew may actually be planted along with annual crops in a mixture, or intercropping with annual crops may be carried out within mature plantations if the spacing between trees is sufficiently wide. Other trees, which may be intercropped, are citrus fruits (mainly oranges), mango and coconuts (Bennett et al., 1979b).

The greater part of the cultivated land is rain-fed, but many villages also utilize groundwater in the more fertile valley land. Only about 1% of the arable land cultivated by peasants is ploughed by tractor and there is very little use of draught oxen. The average area cultivated per family is 2.39 ha (Bennett et al., 1979b). However land fragmentation has reduced the area to 0.4 to 2 ha in highly populated areas such as the Makonde plateau (Tenga, 2006).

The rotation system is based on a bush fallow. Traditionally the bush fallow system consists of 3-4 years cropping followed by 6-9 years fallow during which time the bush regenerates and fertility is restored (Gillman, 1945). In the traditional cropping sequence, those crops which require the highest level of fertility are planted in the first year to be replaced in subsequent years by crops with lower nutrient requirements. Modifications of this basic system arise because of population pressures, which require a higher proportion of land to be planted with arable crops or the planting of a permanent crop like cashew, which reduces the amount of bush, left to regenerate. In some areas, cultivation cycles have now become

very short (3 years of fallow) (Dondeyne, 2004) or cropping is continuous and surviving vegetation consists of early stage thicket regrowth and scattered relict woodland trees (Bennett et al., 1979b).

### 4.4.2. Land use change

Although land use change has not been mapped or examined for the whole study area, Tenga (2006) made several case studies in Mtwara region. He concluded that between 1965 and 2004 area under fallow bushland, fallow bushed grassland, reserved wooded grassland and reserved woodland decreased because of increase in agricultural land use system.

Geomorphic and soil characteristics are the major biophysical factors influencing dominant land use system pattern and change in the region (Bennett et al., 1979b, Tenga, 2006). Altitude is the main geomorphic characteristic determining location of major agricultural land use system. For example, cashew growth is restrained to regions below 800m asl, and it grows best on the nutrient-poor sandy soils of the plateaus (Ngatunga, 2001). The pressure on land resources due to human population increase explains to some extent the land use systems changes in the study area, especially on the densely populated Makonde Plateau. Demographic change, land tenure and farming practices were the socio-economic drivers of the observed land use systems change. Land fragmentation, shifting cultivation and shortening of fallow period are attributed to population increase and land tenure system in the study area whereby acquisition of land is by inheritance (Tenga, 2006).

## 4.5 Problem statement and aim

From the literature, it can be concluded that human impact has tremendously changed land use in Tanzania. Several authors have described the land use systems and changes in the study area. However, to estimate the influence of land use change on SOC stocks in the region, a recent land use map is necessary and the actual change in land use over different time spans has to be calculated. Mapping land use and land cover can be based on the interpretation of aerial pictures or satellite images. Recently several efforts have already been made to make continental and global land use/land cover maps based on satellite images. It has to be checked whether these classifications are useful for a regional C study. By comparing maps from different periods, it is possible to estimate changes in land use over time.

## 4.6 Materials and methods

### 4.6.1. Available maps

#### *4.6.1.1. Original vegetation: ecoregions*

The distribution of eco-regions represents the natural situation, before human impact. It consists of mangrove forests, forests and woodlands (Figure 4.2 and Figure 4.3a).

#### *4.6.1.2. Land use of 1997: Africover*

A digital georeferenced database on land cover and baseline geographic data for the whole of Africa was developed by the Africover initiative (www/africover.org). The purpose of the Africover landcover

database is to provide the information required for natural resource assessment and management, environmental modelling and decision-making. The methodology, operational procedures and software tools for the land cover analysis in the Africover program have been developed by the Africover Eastern Africa module under the financing of the Italian Cooperation. The Eastern Africa module is the first operational component of the Africover Project; it was formulated to meet several African countries' request for assistance in the set-up of reliable and georeferenced databases on natural resources. It is part of FAO assistance to the Nile Basin countries. The Multipurpose Africover Database for the Environmental Resources (MADE) is produced by FAO at a 1:200,000 scale (1:100,000 for small countries and specific areas).
Tanzania is one of the 7 countries of which data bases have been completed and delivered. The land cover was interpreted from LANDSAT imagery (Bands 4,3,2) acquired mainly in the year 1997, verified by field work, digitised, checked for topological and attribute errors and mosaiced. The land cover classes have been developed using the FAO/UNEP international standard LCCS classification system.
The study area is covered by 61 major classes and 138 mixed classes. The ratios of each land use in the mixed classes are given. To make it easier to use and to compare it to other classes, this map had to be reclassified to a smaller number of land uses, which are important in a SOC study.

#### *4.6.1.3. Land use of 2005: Globcover*

The most recent available land cover map is from the ESA Globcover Project led by MEDIAS-France/POSTEL (http://www.esa.int/due/ionia/globcover). It is a land cover map for the period December 2004 - June 2006, derived by an automatic and regionally tuned classification of a MERIS FR time series. It is a global land cover map at 300m resolution with 22 land cover classes defined with the LCCS. The map projection is a Plate-Carrée (WGS84 geoid). The Globcover land cover product has been designed to be a global, consistent land cover map. Therefore, its global legend is determined by the level of information that is available and that makes sense at the scale of the entire world. It is however obvious that the real world is far more heterogeneous than this model of the world with 22 classes. The overall accuracy weighted by the class area reaches 73 % using 3167 points globally distributed and including homogeneous and heterogeneous landscapes.

This is a land cover map and therefore not always useful for this specific study. For example, cashew groves and natural woodlands are in this classification both defined as a certain type of woodland. However, it is expected that the soil C stock in both land uses is very different. Therefore, a distinction should be made between these two. The 354 new profile descriptions in 88 villages that we made during a field survey in 2005 (see paragraph 2.3.1) were used to recalibrate the map using pre-defined land use classes. A reclassification table was made between the two classifications, and the accuracy was determined. Inaccuracies are expected from the following sources:

- The resolution of the map: at 300m small fields can be overlooked. In the highly populated Makonde plateau, the majority of the farmers' fields are 0.4 to 2 ha (Tenga, 2006).
- Time span: the map was made based on satellite images from 2004-2006, but the exact moment is not known for this region. In a land use system were land occupation shifts every few years, the land use in 2004 could be different from that in 2006.

### 4.6.2. Calculation of land use area

The three reclassified maps were digitised in Arcview. The area of the land use classes of each map are calculated by vertical projection. Post-classification change-detection is conducted by comparing the area of each land use on different maps. The conversion from certain land use classes of one map to other classes in another map was calculated by intersecting two maps. Land use changes were also calculated for each land unit (as defined by Bennett et al., 1979a; see Figure 2.4).

## 4.7 Results:

### 4.7.1. Reclassification

The maps are reclassified using 8 main land use groups (Figure 4.3), which could be important in a SOC study. These main land use groups are defined as follows in order to maximally fit the land cover/land use groups of the available maps:

- Forest: >5m height, >40% canopy closure; evergreen, remnants of the Coastal Dry Forest.
- Mangrove forests: regularly flooded trees (>5m) and shrubs (<5m) (brackish water).
- Woodlands: >5m height, 15-40% canopy closure, mainly 'Miombo' type of woodland.
- Bushland/thicket: <5 height, >15% canopy closure, often secondary vegetation.
- Grassland: grass with sometimes scattered trees, <15% canopy closure.
- Cropland: mixed cropping and herbaceous crops, mostly rainfed.
- Tree crops: >1m height, mainly cashew groves and a few mango and coconut fields.
- Other: urban areas, bare ground, inland water.

The 'original' land cover, which is represented by the natural vegetation of the ecoregions, consists of forests, woodlands and mangroves (Figure 4.3a).
The 61 classes of the Africover database are regrouped into the main 8 classes. For example the land use class 'shrubland/thicket' consists of 4 Africover classes: 'open general shrubs with closed to open herbaceous vegetation', 'very open shrubs with closed to open herbaceous vegetation', 'open shrubs with closed to open herbaceous vegetation and sparse trees', and 'closed shrubs'. Mixtures between all groups occur and the respective ratios of each group are known, although on the map only mixed classes of natural vegetation and crops or tree crops are shown on the map with striped patterns (Figure 4.3b).
Based on the 354 reference points the Globcover land cover map was reclassified as in Table 4.2. The accuracy is generally high, except for the shrubland/thicket, which has only 16 reference points. Four main classes and 3 mixed classes were formed (Figure 4.3c). Attention has to be paid to the 5$^{th}$ class, which is defined as a mosaic of woodland, shrubland and tree crops, since this category covers a large part of the study area. The relative amounts of woodland, shrubland and tree crops are calculated based on all sample points together. However, it is possible that in some areas woodland is predominant, while in others more tree crops are growing. For example on the highest parts of the Makonde and Lindi plateaus, no cashew is grown, but this is not reflected in the land use map. It is also expected that the northern regions, which are less populated, have a higher ratio of woodland. However, this could not be verified

with our data. Therefore, the fixed ratio of 30% woodland/25% shrubland/45% tree crops is used for the whole unit, but the previously discussed aspects are kept in mind.

***Table 4.2 Reclassification of land cover classes from Globcover to land use classes.***

| Globcover land cover classes | Reclassification | N° of samples | Accuracy |
|---|---|---|---|
| Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m). | Forest | 2 | 100 |
| Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporary) - fresh or brackish water. | Mangrove | 1 | 100 |
| Open (15-40%) broadleaved deciduous forest/woodland & Open (15-40%) needleleaved deciduous or evergreen forest (>5m). | Woodland | 32 | 63 |
| Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (< 5m). | Bushland/thicket | 16 | 50 |
| Closed (>40%) broadleaved deciduous forest (>5m) | Mosaic of woodland (30%), bushland (35%) & tree crop (45%) | 101 | 72 |
| Mosaic vegetation (grassland/shrubland/forest) (50-70%)/ cropland (20-50%). | Mosaic of tree crops (56%) & crops (44%) | 121 | 86 |
| Rainfed croplands. | Mosaic of crops (60%) & tree crops (40%) | 67 | 91 |

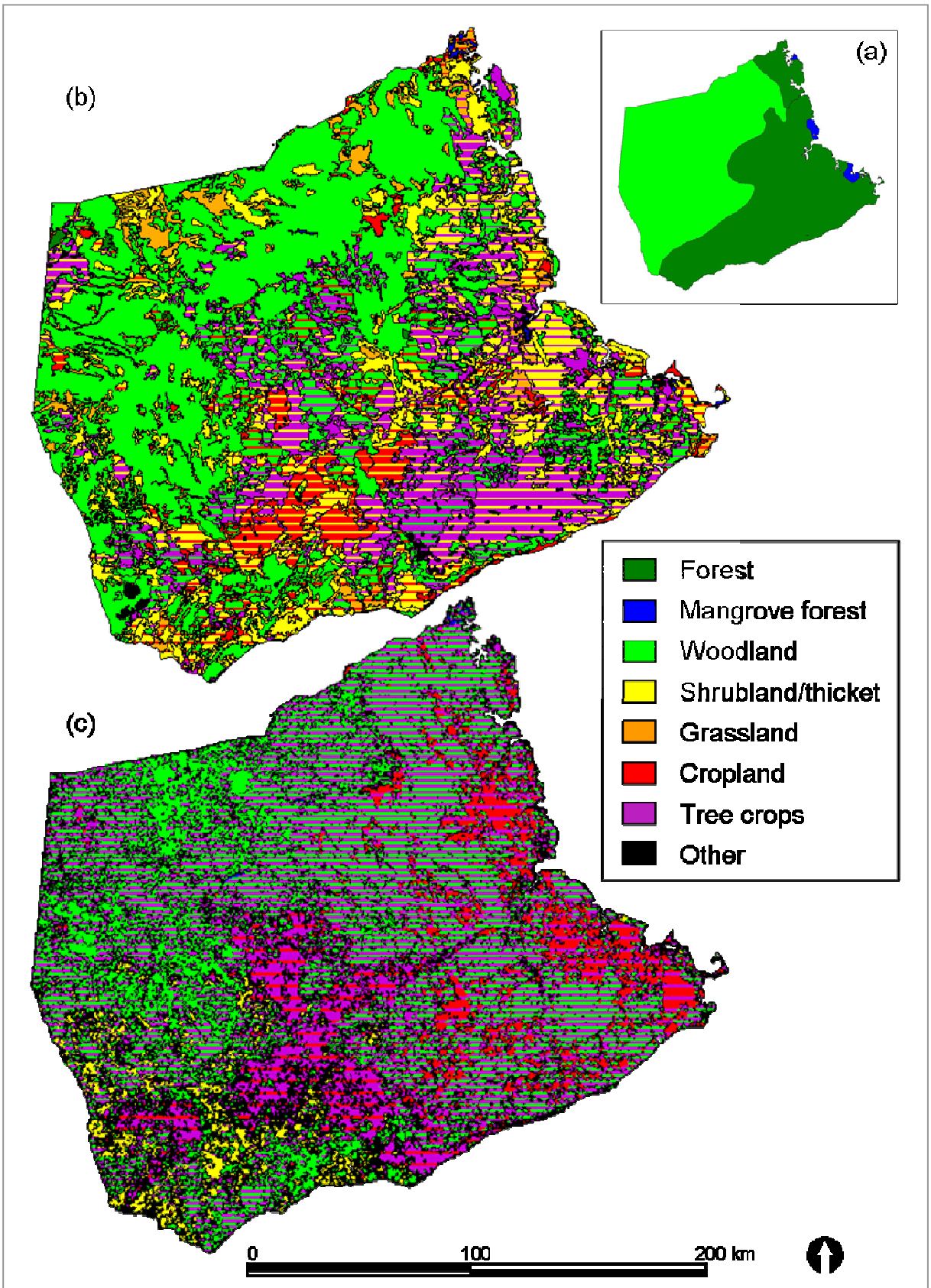



*Figure 4.3 Land use maps based on (a) ecoregions (NGS & WWF, 2009) representing the natural vegetation, (b) land use in 1997 (Africover) and (c) land use in 2005 (Globcover). Striped units represent mixed classes of natural vegetation and farmers' fields.*

## 4.7.2. Area of land use/land use change

Table 4.3 shows the extent of change for each land use class in the three maps. The original coastal dry forest, which was assumed to cover almost half of the study area, has been reduced to only 1.6 kha. On the other hand, the total area of woodland has not been affected much. Both areas of cropland and tree crops have more than doubled in size between 1997 and 2005. The decrease in shrubland/thicket area, which is of secondary nature and often part of the traditional fallow system, might signify a reduction of the fallow period and an expansion to more permanent agriculture. The results will be discussed in greater detail by considering which class has been converted to which other.

***Table 4.3 Land use (kha and %) in the various maps.***

| Land use | original vegetation (Ecoregion) | 1997 (Africover) | 2005 (Globcover) |
|---|---|---|---|
| **Forest** | 202.5 (48.2%) | 1.6 (0.4%) | 1.6 (0.4%) |
| **Mangrove** | 3.7 (0.9%) | 0.2 (0.04%) | 0.8 (0.2%) |
| **Woodland** | 213.8 (50.9%) | 198.0 (47.1%) | 142.9 (34.0%) |
| **Shrubland/thicket** | | 101.2 (24.1%) | 74.1 (17.7%) |
| **Grassland** | | 23.2 (5.5%) | |
| **Crop land** | | 26.7 (6.4%) | 61.7 (14.7%) |
| **Tree crops** | | 66.9 15.9%) | 137.3 (32.7%) |
| **Urban** | | 2.1 (0.5%) | 1.5 (0.4%) |

Table 4.4 presents the conversion from the original natural vegetation to the situation in 1997. The 5 most important land uses that have replaced the original land cover class are shown. The coastal forest has largely been replaced by secondary bushland, thicket and woodlands. It is on the original forest-land that most agriculture has been established: 8% of the area has been converted to cropland and 23% to cashew groves. In the mangrove forests, the same general trend was observed. The original woodland area has been largely preserved. The main land use conversion was to secondary shrubland. Only 15% of this land was converted to agriculture with (tree) crops.

Table 4.5 depicts the main classes of land use change between 1997 (Africover map) and 2005 (Globcover map). Some of the land use changes may be artefacts because of the classification by different authors. For example according to the data, the area of grassland has been largely replaced by woodland. Several authors have described the current vegetation in these areas as a complex mixture of vegetation types such as woodland, bushland, shrubland and wooded grassland in various stages of secondary development, which are the result of a long history of disturbance (Bennett et al., 1979a; NGS & WWF, 2009). Such vegetation mixtures can easily be interpreted as woodland by one author and as wooded grassland by another.

More than half of the woodland/shrubland/grassland vegetation area of 1997 remains. The rest has been replaced mainly (almost 100 kha) by tree crops (cashew). Only 23% of the cropland remains in the same location, and cropped area extends on previous woodland/shrubland/grassland.

***Table 4.4 Land use change between the original vegetation and 1997 (kha and %).***

| Ecoregion (original vegetation) | | Africover (1997) | | % of original |
|---|---|---|---|---|
| **Forest** | 202.5 | Bushland/thicket | 67.0 | 33 |
| | | Woodland | 60.0 | 30 |
| | | Tree crops | 47.5 | 23 |
| | | Cropland | 16.6 | 8 |
| | | Grassland | 8.0 | 4 |
| **Mangrove** | 3.7 | Woodland | 1.4 | 37 |
| | | Bushland/thicket | 1.0 | 28 |
| | | Tree crops | 0.7 | 20 |
| | | Cropland | 0.7 | 18 |
| | | Grassland | 0.4 | 10 |
| **Woodland** | 213.8 | Woodland | 135.7 | 63 |
| | | Bushland/thicket | 31.7 | 15 |
| | | Tree crops | 20.1 | 9 |
| | | Grassland | 13.9 | 6 |
| | | Cropland | 10.0 | 5 |

***Table 4.5 Land use change between 1997 and 2005 (kha and %).***

| Africover (1997) | | Globcover (2005) | | % of 1997 cover |
|---|---|---|---|---|
| **Woodland** | 198 | Woodland | 84.54 | 43 |
| | | Tree crops | 57.78 | 29 |
| | | Shrubland/thicket | 36.95 | 19 |
| | | Cropland | 16.44 | 8 |
| **Shrubland/ thicket** | 101.2 | Woodland | 27.91 | 29 |
| | | Tree crops | 34.83 | 34 |
| | | Cropland | 18.18 | 18 |
| | | Shrubland/thicket | 16.12 | 17 |
| **Grassland** | 23.2 | Woodland | 10.92 | 44 |
| | | Tree crops | 5.80 | 25 |
| | | Shrubland/thicket | 6.00 | 24 |
| | | Cropland | 1.92 | 8 |
| **Cropland** | 26.7 | Tree crops | 9.52 | 36 |
| | | Woodland | 6.55 | 24 |
| | | Cropland | 6.21 | 23 |
| | | Shrubland/thicket | 4.85 | 18 |
| **Tree crops** | 66.9 | Tree crops | 28.16 | 42 |
| | | Cropland | 18.35 | 27 |
| | | Woodland | 12.67 | 19 |
| | | Shrubland/thicket | 8.26 | 12 |

The fact that one land use is replaced by another and vice versa, suggests that a shift in land use through the study area has occurred. Therefore, the land use/land use change for the 3 periods in the different land units will be discussed (Table 4.6). Only the most important land uses (together covering 80% or more of the land unit) are given in the table.

The whole coastal area was originally covered by coastal forest, with some patches of mangrove forest. In 1997 much of the area was still covered by shrubland, with some grassland and woodland. Tree crops and crops were mainly grown in the river valleys. However, in 2005, tree crops are the most important land uses in almost all coastal land units, and croplands cover often more than 20% of the area.
On the plateaus of Mtwara, tree crops are the most important land use in 1997 and 2005. Cropland becomes only important after 1997. In the more northern plateaus, woodland and shrubland remain important land uses, although their area is strongly reduced in size on the favour of the increasing tree crops. Cropland is still unimportant here. In the fertile Ruvuma valley, at the southern border of the Mtwara plateaus, cropping is very important, although here also the area of cashew has increased.
In 1997, the forest area of the southern plains has been replaced by shrubland, while the woodland area of the more northern plains remained woodland for often more than 50%. The area of tree crops in 1997 expanded in the Lulindi, Nachingwea-Masasi, Mnero-Ruangwa and Mid-Mbwemkuru Plains. Cropping was only important south of the Lukuledi River. In 2005, tree crops covered 20 to 40% of the plains. Cropland is still unimportant, except for the Lulindi and Nachingwea-Masasi plains.

# 4.8 Discussion

## 4.8.1. Land use/land use change

### *4.8.1.1. Coastal zone*

Whereas the original vegetation of the coastal area consisted of coastal forest with patches of mangrove forest, shifting cultivation has had a severe impact on the original vegetation, which is largely secondary in character, covering a multitude of small areas in every stage of development. Population pressure in some parts of the coastal plain has reduced the usual long-term fallow periods to 2-4 years or eliminated them completely (Bennett et al., 1979a). Bennett et al. (1979a) confirm that in the whole coastal area forest is likely to develop in this climatic condition if not impeded by poor soil conditions and/or periodic man made disturbance. In 1997 the most important land use in the coastal plains is a bush fallow, in the form of shrubland and thicket and several areas of very open wooded grassland near the coast on the Kilwa and Mchinga Coastal plains. In the bush fallow, canopy closure may be 90-100% and there is often no herbaceous ground cover (Bennett et al., 1979a). Patches of upland woodland are found in the coastal plains of Kilwa district and at the edge of the Makonde dissected plateau, where there have been less disturbances and good soil conditions for forest development. In 2005 woodland and bushland only remains relatively important in the northern plains.

***Table 4.6 Main land use (%) for landunits in the 3 periods.***

| | Landunit | natural vegetation (Ecoregion) | 1997 (Africover) | 2005 (Globcover) |
|---|---|---|---|---|
| **Coastal area** | Kilwa Dissected Plain | 100% Forest | 31% Shrubland, 23% Woodland, 21% grassland | 44% Tree crops, 23% Woodland, 18% Shrubland |
| | Pande Coastal Plain | 92% Forest, 8% Mangrove | 38% Woodland, 34% Tree crops, 17% Shrubland | 41% Tree crops, 24% Cropland, 19% Woodland |
| | Kiswere Dissected Zone | 99% Forest | 49% Shrubland, 31% Woodland | 39% Tree crops, 34% Woodland, 20% Shrubland |
| | Mchinga Coastal Plain | 100% Forest | 45% Shrubland, 30% Woodland, 17% Tree crops | 40% Tree crops, 28% Cropland, 19% Woodland |
| | Mchinga Hills | 100% Forest | 54% Shrubland, 29% Woodland | 42% Tree crops, 38% Cropland |
| | Lindi Coastal Plain | 91% Mangrove, 9% Forest | 27% Shrubland, 25% Grassland, 20% Woodland | 41% Tree crops, 27% Cropland, 20% Woodland |
| | Lindi Ridge | 92% Forest, 8% Mangrove | 52% Shrubland, 15% Tree crops, 14% Cropland | 42% Cropland, 41% Tree crops |
| | Mambi Plain | 100% Forest | 65% Tree crops, 17% Cropland | 41% Cropland, 41% Tree crops |
| | Lukuledi Dissected Plain | 100% Forest | 44% Shrubland, 27% Tree crops, 19% Grassland | 43% Tree crops, 21% Woodland, 19% Cropland |
| | Mtwara Coastal Plain | 87% Forest, 13% Mangrove | 50% Shrubland, 17% Woodland, 13% Tree crops | 39% Tree crops, 31% Cropland, 14% Shrubland |
| | Rutamba Valley | 100% Forest | 83% Tree crops | 40% Tree crops, 20% Woodland, 18% Cropland, 15% Shrubland |
| | Mavuji Valley | 100% Forest | 24% Cropland, 24% Mangrove, 18% Grassland | 32% Tree crops, 24% Cropland, 23% Mangrove |
| | Mbwemkuru Alluvial Plain | 69% Woodland, 31% Forest | 38% Woodland, 19% Shrubland, 17% Grassland | 40% Tree crops, 32% Cropland, 19% Woodland |
| | Lukuledi Valley | 100% Forest | 44% Tree crops, 21% Shrubland, 18% Cropland | 40% Tree crops, 35% Cropland, 18% Woodland |
| **Plateaus** | Kilwa Uplands | 75% Woodland, 26% Forest | 88% Woodland | 43% Tree crops, 27% Woodland, 20% Shrubland |
| | Liwale Uplands | 100% Woodland | 60% Woodland, 13% Tree crops, 13% Shrubland | 60% Woodland, 24% Tree crops |
| | Lindi Plateaux and Valleys | 93% Forest, 7% Woodland | 52% Woodland, 23% Shrubland, 17% Tree crops | 41% Tree crops, 26% Woodland, 17% Shrubland |
| | Makonde Dissected Plateau | 98% Forest | 36% Tree crops, 36% Shrubland, 25% Woodland | 42% Tree crops, 29% Cropland, 15% Woodland |
| | Makonde Plateau | 98% Forest | 39% Tree crops, 24% Shrubland, 23% Woodland | 42% Tree crops, 24% Cropland, 18% Woodland |
| | Makonde Platform | 68% Forest, 32% Woodland | 39% Shrubland, 33% Woodland, 13% Cropland | 44% Tree crops, 22% Woodland, 20% Cropland |
| | Basement Hills | 66% Forest, 34% Woodland | 66% Woodland, 19% Tree crops | 37% Tree crops, 32% Woodland, 17% Cropland |
| | Ruvuma Floodplain | 100% Forest | 37% Cropland, 21% Grassland, 21% Shrubland | 39% Tree crops, 26% Cropland, 24% Woodland |
| **Plains** | Lulindi Plain | 100% Forest | 41% Shrubland, 29% Cropland, 23% Tree crops | 46% Tree crops, 36% Cropland |
| | Southern Masasi Plain | 87% Forest, 13% Woodland | 36% Shrubland, 34% Woodland, 17% Cropland | 38% Woodland, 33% Shrubland, 19% Tree crops |
| | Nachingwea-Masasi Plain | 89% Woodland, 11% Forest | 36% Woodland, 27% Shrubland, 21% Tree crops | 36% Tree crops, 30% Woodland, 23% Cropland |
| | Mnero-Ruangwa Plain | 96% Woodland, 4% Forest | 53% Woodland, 31% Tree crops | 40% Tree crops, 31% Woodland, 15% Cropland |
| | Upper Mbangala Plain | 100% Woodland | 69% Woodland, 16% Shrubland | 45% Woodland, 31% Shrubland, 20% Tree crops |
| | Inselberg Plain | 100% Woodland | 58% Woodland, 23% Shrubland | 43% Shrubland, 28% Woodland, 21% Tree crops |
| | Lower Mbwemkuru Dissected Pl. | 100% Woodland | 82% Woodland | 42% Woodland, 36% Tree crops, 18% Shrubland |
| | Upper Mbwemkuru Plain | 100% Woodland | 70% Woodland, 14% Shrubland | 57% Woodland, 23% Shrubland |
| | Matandu-Mavuji Plain | 100% Woodland | 78% Woodland, 14% Shrubland | 62% Woodland, 24% Tree crops |
| | Liwale Plain | 100% Woodland | 76% Woodland, 8% Shrubland | 60% Woodland, 25% Tree crops |
| | Mid-Mbwemkuru Dissected Plain | 100% Woodland | 78% Woodland, 11% Tree crops | 57% Woodland, 25% Tree crops |

The main agricultural activities in the coastal area in 1979 are described by Bennett et al. (1979b). In the coastal plain cassava, sorghum, and to a lesser extent maize, are the main food crops. Total bush clearing was carried out for cash crops, mainly cashew that was planted on the sandy crests of hills and ridges. The coastal hills are a sparsely populated zone with little agricultural activity. Sorghum appears to be the main food crop grown. In the coastal dissected plain the alluvial valleys and floodplains are the most important areas agriculturally; they are also the more populated areas of the zone. In the wetter areas, rice is the most important crop grown while the drier ground is planted with sorghum, sesame, pigeon peas and maize. Where valley land occurs in relatively small pockets, cultivation is continuous, but where such land is plentiful it is cultivated for about 4 years and fallowed for anything up to 20 years (Bennett et al., 1979a, 1979b).

In 1997 cropland and tree crops are important land uses in the river valleys. However, in the plains and hills, tree crops never cover more than one third of the area and croplands remain below 15%. According to Bennett et al. (1979b) soil factors are the main constraints to development: sandy infertile soils in the plain, dark cracking clay soils which are difficult to manage in the hills and dissected plains and high pH and phosphate or trace element fixation when calcium or sodium contents are high. Bennett et al. regarded the area as having a low potential and little scope for expanding production. However, it can be seen that agricultural expansion in the coastal area has still increased by 2005. In the fertile river valleys, the area of cropland increased, often by 15% or more, for example in Rutamba valley, Mambi plain and Lukuledi Valley, while the area of tree crops remained more constant compared to 1997. In areas with dark cracking clays such as the Kiswere dissected zone, woodland and bushland still cover most of the area. On the sandy Luvic Arenosols of some of the northern coastal plains, woodland, tree crops and cropland are the most important. However, in areas with fertile soils such as the Umbric Alisols of the Mtwara Coastal Plain, an area increase occurred for both tree crops (+26%) and cropland (+20%).

#### *4.8.1.2. Plateaus and dissected plateaus*

Whereas the Makonde and Lindi plateaus were formerly covered by coastal forest, woodland was the natural vegetation type of the more northern Kilwa and Liwale uplands.

The vegetation of the Makonde Plateaus has been degraded by many years of shifting cultivation. Surviving vegetation consists of early stage thicket regrowth and scattered relict woodland trees (Bennett et al., 1979a). In 1979 on much of the Makonde plateau an in situ bush/fallow sequence is practiced based on a 6-9 year fallow period with a 3 year cropping cycle, although intense population pressure is leading to shorter fallow periods and continuous cultivation in many areas. Except at higher altitudes, cashew is the predominant crop and most important cash crop. Cassava is the main food crop, although rice is often the preferred staple (Bennett et al., 1979b). In 1997 as well as 2005, tree crops are still the most important land use. Cropland becomes only one of the main land uses after 1997. Soils are sandy and nutritionally poor, being completely weathered and strongly leached with low water holding capacity. The only nutrients available occur in the surface organic matter. The groundwater level is very low; supplies of water for domestic purposes and livestock are few and water often has to be carried long distances (Bennett et al., 1979b). However, the large expanse of agriculture is not the result of good soil conditions, but of a high population pressure, which has been initiated historically by the migration of the Makonde people (see paragraph 2.2.1). A decrease in population in the overpopulated areas would allow land to

return to bush, a fallow period to be included in the cultivation cycle, and a measure of fertility to be restored in the soil (Bennett et al., 1979b). In the fertile Ruvuma valley, at the southern border of the Mtwara plateaus, cropping is very important, although here as well the area of cashew has increased.

The more northern plateaus have been less influenced by human disturbance than the Makonde plateau. According to Bennett et al. (1979a), patches of relict forest or forest-woodland occur in the Rondo forest reserve and on several of the other Lindi plateaus. In 1979, the plateau vegetation north of Rondo consists of several types of moderately dense to closed woodland and dense to light thicket with few emergent trees. The flanks of the plateaus and the valleys separating them are grown over with a woodland-bushland complex. The chief cash crop on the more northern plateaus is again cashew, except for the Rondo plateau. The main food crops are sorghum, maize, and to a lesser extent cassava. The usual length of the fallow period increases northwards (Bennett et al., 1979b). In 1997, woodland and to a smaller extent shrubland remain the most important land uses, although tree crops are already covering 17% of the Lindi plateau and 13% of the Liwale uplands. Cropping is rare on these plateaus. Towards 2005, the area of tree crops has increased to 24% in the Liwale uplands, 41% on the Lindi plateaus and valleys and 43% in the Kilwa Uplands. Cropland is still unimportant. A small patch of relict forest still remains on the Rondo plateau and in the Liwale uplands.

#### *4.8.1.3. Plains*

Although forest formed the original vegetation cover of the southern plains, Bennett et al. describe the vegetation in 1979 as a woodland-bushland complex which tends to be lower in stature and more thinly distributed than floristically similar communities to the north and east. Farmers changed some areas steadily into agricultural land. Later on the popularity of cashew as a cash crop has transformed many small-scaled rotational fields in large cashew plantations. This is the only area where groundnuts are also an important cash crop, besides cashew and sesame. Cassava and sorghum are the main food crops (Bennett et al., 1979b). Expansion with croplands and tree crops occurred mainly at the edge of the Makonde Plateau (Lulindi Plain and eastern part of the Southern Masasi Plain). In 2005 the natural vegetation of the Lulindi Plain has almost completely disappeared while in the Southern Masasi plain only 38% of woodland remains.

The larger plains stretching northwards are characterized by extreme seasonal fluctuations in soil moisture and are thus generally unsuitable for forest growth. The natural vegetation cover here is woodland. Bennett et al. (1979a) described an alternating pattern of woodland-bushland in higher ground and wooded-grassland in the drainage lines, dotted with large termitaria, which rise well above flood levels and provide suitable microhabitats for trees bushes. The area of western Lindi, eastern Nachingwea and northeastern Masasi, which consists of fertile Nitisols, has great agricultural potential. The main food crops are maize and sorghum and the main cash crops are cashew and sesame (Bennett et al., 1979b). Indeed, in 1997 and 2005 this area is completely used for cropland and tree cropping. In 1979, the rest of the central plain area was sparsely populated and there was little agricultural activity although the rest of the Nitisols had a high agricultural potential (Bennett et al., 1979b). Indeed, in 1997 small areas of Nitisols along the Mbwemkuru river (in the Mid-Mbwemkuru dissected plain) are being occupied by tree crops. The rest of the northern plains remain covered with wood- and shrubland. This area has expanded in 2005 to the whole Nitisol area and surroundings, with tree crops covering more than 20% of the area. Only in

the Upper Mbwemkuru Plain, Liwale Plain and Matandu-Mavuji Plain, furthest removed from these fertile soils, does woodland still cover around 60% of the area. Cropland is not important here.

### 4.8.2. Comparison with national data

Now it is possible to compare the land use of the study area in southeastern Tanzania with the national data for Tanzania. Since the available national dataset (Figure 4.1) dates from 1996, it will be compared to the Africover dataset of 1997 of the study area.
The areas of woodland (47.1%) and shrubland/thicket (24.1%) in the study area are comparable to those of Tanzania (respectively 40% and 18%). The area of grassland (5.5) is considerably lower than in Tanzania (20%). The natural vegetation of the study area consists after all of forest and woodland. While the cropland is less extended than elsewhere (6.4% versus 9% nationally), tree crops cover 15.9% of the total area, which is 10 times more than in the whole country. This is logical since southeastern Tanzania is the main producer of cashew in the country.

The results also confirm the findings of Tenga (2006) and CEEST (1994) that areas under natural vegetation decreased because of an increase in agricultural land use systems across all land units.

## 4.9 Conclusions

This study proves that natural vegetation has been cleared for the establishment of cropland and tree crops in the whole study area. Two main types of natural vegetation can be distinguished: coastal forest used to cover the whole coastal area, Makonde and Rondo plateaus and the southern part of the plains, while Miombo woodland was growing in the rest of the area. The coastal forest has suffered most of human intervention. The reason is the greater population in these areas, which is a historical development. Despite its high ecological value, only 0.4% of the natural forest remains, mainly in the Rondo forest reserve. The rest was gradually converted to secondary vegetation, tree crops and cropland. Secondary shrubland covered most of the coastal area in 1997, with crops and tree crops growing mainly in the river valleys. Towards 2005, only in the northern area important areas of woodland were preserved. The area of cropland extended considerably, while tree crops were grown on the more infertile sandy soils. The Makonde plateau was already in 1997 densely populated, and forest was cleared mainly for cashew, except on the higher elevations. In 2005 this area was expanded more and complemented by more than 20% of cropland. The Rondo plateau has always been less populated and some of the original forest area could be preserved, but tree crops have been introduced largely. In the southern plains, cropland and tree crops have replaced the forest vegetation, especially in the eastern part towards the Makonde plateau.

The rest of the plains and the northern plateaus were formerly covered in woodland, since the extreme seasonal fluctuations in soil moisture were unsuitable for forest growth. Although the total area of woodland in the study area has not much declined, large parts of it have been disturbed and been converted to secondary vegetation. In the large plains, areas with tree crops have expanded mainly on the fertile Nitisols. The rest of the area still remains largely under woodland cover.

The large expanse of cashew groves is typical of southeastern Tanzania, where most of the nation's cashew is produced. However, it is expected that these land use changes will have had a serious impact on the regional soil C stocks. This will further be discussed in Chapter 6.

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# 5 Methodological Aspects of Measuring SOC

# 5.1 Introduction

Soil organic carbon (SOC) is measured in the laboratory as the mass of C per oven-dry soil mass (%C), but for up-scaling to land units it is usually expressed as a C density. The C density is the C mass per soil volume (g $C.m^{-3}$), which is equal to the C mass per land area (in g $C.m^{-2}$ or Mg $C.ha^{-1}$) for the sampling depth (m). Multiplying the C density of a land unit (in Mg $C.ha^{-1}$) by the area of this land unit (in ha) gives the total SOC stock of the land unit (in Mg C).

The C density of a soil profile is calculated by summing up C densities for each horizon as follows:

$$SOC_d = \sum_{horizon=1}^{horizon=n} SOC_{d,horizon} = \sum_{horizon=1}^{horizon=n} (\%C \times BD \times Depth \times (1 - frag))_{horizon} \qquad \textbf{Equation 5.1}$$

with $SOC_d$ = soil organic carbon density of the land unit of interest (Mg $C.ha^{-1}$), $SOC_{d,horizon}$ = soil organic carbon density for a constituent soil horizon (Mg $C.ha^{-1}$), %C = concentration of soil organic carbon in a given soil mass obtained from lab analyses (g $C.(100g\ soil)^{-1}$), BD = soil mass per sample volume (g $soil.cm^{-3}$), Depth = horizon depth or thickness of soil layer (m), frag = % volume of the coarse fragments/100 (dimensionless) (IPCC, 2003). It is also possible to model the variation of SOC with soil depth and to calculate a definite integral of the fitted model (Jobbágy & Jackson, 2000). This can be calculated to a certain soil depth. IPCC (2003) recommends calculating carbon densities for a given soil depth or layer, e.g. 100 cm or the 0-30 cm layer. This method is most effective when most of the SOC is contained in the sampling depth but may overestimate SOC in high bulk density soils. This is particularly problematic when treatments, such as tillage, affect bulk density. One solution to this problem is to express the quantity of SOC on an equivalent mass basis (Ellert et al., 2002). Volumetric measurements are corrected by adjusting the sampling depth to give an equivalent mass. This is done by sampling a smaller depth in heavier soils or a greater depth in lighter soils. However, in order to compare our results to those found in literature, we calculated SOC stocks to a fixed depth of 1m. The effect different bulk densities could have on this result will be discussed in the next chapter.

Equation 5.1 should make it easy to calculate SOC stocks from the 3 existing soil datasets and the new dataset obtained by the author in 2005, which were introduced in paragraph 2.3.1. However, the cost and time necessary for making numerous systematic measurements of C content and bulk density down to a sufficient depth are major constraints, and not all information is available for every dataset. Moreover, these variables can be measured using different techniques, which are not always consistent with each other (Table 5.1). SOC was measured with wet combustion (Walkley & Black method) by Bennett and Ngatunga (with supplementary heating and photometric determination of chroma) and ITCRP (no specifications given on the method), while loss-on-ignition was used for measuring SOM in the new profiles. Texture analysis was conducted using the pipette method after hydrogen peroxide treatment (Day, 1965) in the studies of Bennett and Ngatunga. No specifications are known on the methodology for measuring soil texture used by ITCRP. In the new dataset the texture is estimated in the field by palpitation. Samples were taken in every horizon of the full soil profile in all datasets except for the new dataset, where only 2 samples were taken at a fixed depth.

***Table 5.1 Availability of soil variables necessary for calculating SOC stocks in different land units, for the four datasets.***

| Author | Number of Profiles | SOC or SOM method | Sampling depth | BD (core method) | Texture | Land use description | Soil type |
|---|---|---|---|---|---|---|---|
| **Bennett et al. (1979)** | 40 | Walkley & Black (SOC) | Every horizon (>1m) | Measured for every horizon | Pipette method | no | Full description (FAO-UNESCO, 1974) |
| **ITCRP (1981)** | 210 | Walkley & Black (SOC) | Every horizon (>1m) | Lacking | Pipette method | Yes, general | Full description (FAO-UNESCO, 1974 |
| **Ngatunga (2001)** | 30 | Walkley & Black (SOC) | Every horizon (>1m) | Lacking | Measured | Yes, in detail | Full description FAO (1990 & 1998) |
| **New profiles (taken in 2005)** | 354 | Loss-on-ignition (SOM) | At 0-5 and 40-45 cm | Measured at 0-5 and 40-45 cm | Palpatation | Yes, in detail | Description WRB (FAO, 2006) |

If the four datasets have to be used for SOC stock estimation, following problems can be formulated based on Table 5.1.

1. SOM values from the profiles of 2005 have to be converted to SOC contents;
2. BD data are lacking from the datasets of ITCRP (1981) and Ngatunga (2001) and have to be estimated;
3. Measurements at two depths in the 2005 profiles have to be converted to a C distribution of the full profile;
4. Total SOC stocks of all datasets had to be calculated.

This chapter will explain the differences between measuring techniques for SOC and SOM and how they can be converted; why BD data are often lacking and how this can be overcome, how soil C is vertically distributed along the profile and how different datasets can be compared despite different measuring techniques used. Finally, SOC stocks of the study area can be calculated from all these datasets, despite the data gaps, using Equation 5.1.

# 5.2 Literature review

## 5.2.1. Soil Organic matter (SOM)

### *5.2.1.1. Definition of SOM*

Soil organic matter (SOM) is defined as the organic fraction of the soil without undecayed plant and animal residues, often used synonymously with humus (SSSA, 1987). It consists in a heterogeneous mixture of interacting polymers (Sposito, 1989). SOM originates from C fixed by plants delivered to the soil in the form of leaf and wood litter, roots and root exudates. The definition seems too restrictive given the fact that most analytical procedures for SOM do not distinguish between decomposed and undecomposed plant and animal residues and living organisms in soils sieved < 2 mm before analysis

(Sikora et al., 1996). In the broadest sense, SOM consists of diverse components such as living organisms, slightly altered plant and animal organic residues, and well-decomposed organic residues that vary considerably in their stability and susceptibility to further decomposition (Magdoff, 1992). As illustrated in Figure 5.1 the majority of SOM is contained in plant and animal debris and soil humus. These non-living components of SOM play an important role in determining the soil physical-chemical environment within which living organism function. Heterotrophic soil microorganisms and fauna, a relatively small proportion of total OM (1-5%), function as important catalysts for transformation and cycling of nutrients (Doran & Smith, 1987). Soil microbial biomass is a significant sink-source for C and N (Jenkinson, 1988). SOM is considered the single most important indicator of soil quality (Larson & Pierce, 1994).

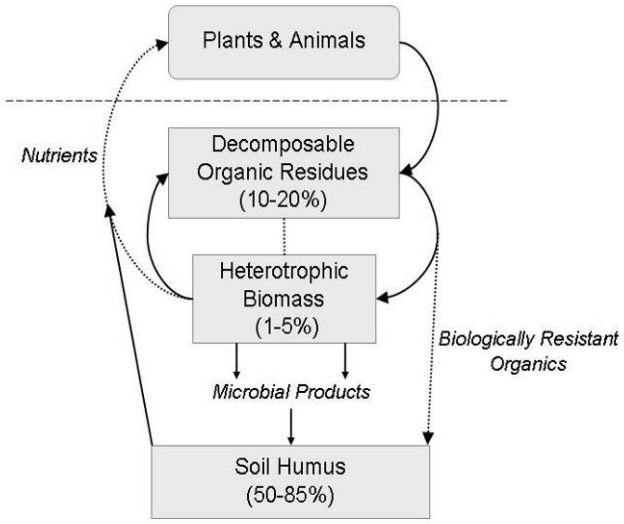



***Figure 5.1 Relationships between living and nonliving soil organic matter components, their role in nutrient cycling and their relative proportion (in %) of total SOC (based on Doran & Smith, 1987).***

### *5.2.1.2. SOM fractions*

SOM has been divided into biologically meaningful C fractions in many different ways. Evans et al. (2001) summarised several partitioning techniques discussed in literature: chemical fractionation, physical fractionation, mineralization, biological fractionation, C dating and analytical techniques. These will be discussed briefly because they give an idea of the constitution of SOM and because these separate fractions are often discussed in literature. Chemical fractionation techniques include the characterisation of dissolved organic matter and water soluble organic matter (Herbert & Bertsch, 1995), hydrolysis for extracting carbohydrates (Lowe, 1993), classical fractionation dividing organic matter into humic acids, fulvic acids and humin (Sposito, 1989), sequential extraction dividing free and complexed SOM (Schnitzer & Schuppli, 1989), oxidation for estimating total soil C concentrations (Walkley & Black, 1934; Schollenberger, 1945) and the use of supercritical fluids for separating labile and recalcitrant pools (Sanchez & Ruark, 1995). Physical fractionation provides information concerning the architecture of SOM: light and heavy fractions are obtained using density fractionation (Strickland & Sollins, 1987), macro-organic matter (Ellert & Gregorich, 1995) and particulate organic matter (Cambardella & Elliot, 1992) are separated from SOM by sieving and/or flotation, particle-size fractionation divides SOM into size classes which are important in determining the stability of SOM (Feller & Beare, 1997), density and particle fractionation schemes have been combined to further define SOM fractions (Hassink et al., 1997) and aggregates may be partitioned from SOM because soil aggregation influences turnover (Degens & Sparling, 1996). Release rates from C mineralization through incubation can be used to estimate C pool sizes (such as active, slow and passive pools) and their turnover rates (Collins et al., 1997). In biological fractionation, it is possible to determine microbial biomass C for monitoring SOM dynamics (Sparling, 1992) and root biomass for its importance in C cycling (Aerts et al., 1992). C-dating with $^{14}C$ can be used

to estimate mean residence time of soil organic C pools in surface soils (Hsieh, 1993) and to determine resistant organic C when it is combined with acid hydrolysis (Paul et al., 1997); the difference between assimilation of the stable isotope $^{13}C$ of $C_3$ (Calvin cycle) and $C_4$ (Hatch-Slack cycle) plants can be used to quantify the contribution of each pathway to SOM in mixed plant communities and to estimate C turnover after certain land use changes (Baledescent et al., 1988) and the oxidizable C ratio is used to determine the age of a C sample (Frink, 1994). Analytical techniques allow the characterization of complex heterogeneous substances: near infrared reflectance spectroscopy (NIR) is an effective method for the determination of lignin, cellulose and C (Wessman et al., 1988), nuclear magnetic resonance (NMR) is used to distinguish between C nuclei in different intramolecular environments and provides detailed information about the chemical structure of SOM (Wilson, 1987), pyrolysis-field ionization mass spectrometry (Py-FIMS) allows for the determination of SOM on a molecular basis (Simmleit & Schulten, 1989; Vancampenhout et al., 2009) and fourier transform infrared spectroscopy (FTIR) may be used to analyse soils quantitatively and semi-quantitatively (McColl & Gressel, 1995).

#### *5.2.1.3. Loss-on-ignition for measuring SOM*

Dry ashing methods have been widely used to estimate SOM contents in soils and sediments (Ball, 1964; Dean, 1974; David, 1988; Heiri et al., 2001; Santisteban et al., 2004; De Vos et al., 2005b). It involves the removal of OM from an oven dry sample (dried at 105°C) by combustion of the sample at medium temperature (375 to 600°C) in a temperature-regulated muffle furnace. The loss-on-ignition (LOI) is defined as the change in mass as a result of heating a sample under specified conditions. Advantages include the large sample numbers that can be run simultaneously and the low cost of equipment (Konen et al., 2002).

Ideally, SOM would oxidize completely within a narrow temperature range at which weight loss from water and soil minerals is negligible. Unfortunately, this is not the case, so drying and ignition temperature selection is somewhat arbitrary but, at the same time, critical to minimize errors. The drying temperature should be high enough to remove a maximum amount of soil water but low enough to prevent loss of OC. Analogously; the ignition temperature should be high enough to remove a maximum amount of OC and low enough to minimize loss of other soil constituents (Schulte & Hopkins, 1996). Reactions of soil constituents, which contribute to weight losses in LOI, are summarised in Table 5.2.

Some errors could be avoided by selecting a temperature above 105°C as the drying temperature but below which organic matter decomposes. Schulte & Hopkins (1996) recommend a drying temperature of 150°C (2h) for soils containing gypsum or hydrated clays. Losses of structural water from clay minerals may be large especially when ignition temperatures are above 450°C (Howard & Howard, 1990). Ball (1964) found that structural water losses could be reduced at 375°C, but at that temperature incomplete ashing was observed (Donkin, 1991). Carbonates remain stable at temperatures below 500°C (Konen et al, 2002). For example, no weight loss was observed from the destruction of $CaCO_3$ when using ignition temperatures between 400 and 530°C and without pre-treatment (Davies, 1974; Ben-Dor & Banin, 1989; Heiri et al., 2001). Therefore, a temperature of 550°C has been suggested (Andrejko et al., 1983; Howard & Howard, 1990) and applied (Bhatti & Bauer, 2002; Konen et al, 2002; De Vos et al., 2005b). Heiri et al. (2001) showed that exposure time and sample size can influence weight loss after ignition at 530°C: only 40-70% of the possible weight loss was reached after 2h of exposure and smaller samples were losing weight faster than larger ones.

***Table 5.2 Summary of soil constituents contributing to weight loss in LOI. Based on: Mackenzie (1957), Ball (1964), Bengstton & Enell (1986), Goldin (1987), Howard & Howard (1990), Harris et al. (1992), Schulte & Hopkins (1996), Sutherland (1998), Dell'Abate et al. (2000), Heiri et al. (2001), Santisteban et al. (2004), Trompowsky et al. (2005).***

| Soil constituent | e.g. | Reaction |
|---|---|---|
| **Organic matter** | | Oxidation and combustion occurs in steps between 190 and 1000°C. The main part is lost between 200-550°C: decomposition of more labile aliphatic and carboxylic groups starts at 300°C; loss of more aromatic groups starts at 400-450°C. |
| **Clay minerals (sheet silicates)** | | Desorption of layer water from Ca-montmorillonite, Ca-vermicullite, muscovite, phlogopite, biotite, pyrophyllite, kaolinite, halloysite and antigorite between 250-350°C.<br>Removal of hygroscopic water of swelling clays (montmorillonite, vermiculite, illite) between 100-250°C.<br>Removal of intercrystalline water (dehydroxylation) begins at 350-370°C, however Na-montmorillonite & vermiculite begin to lose crystal -lattice water at 150-250°C. |
| **Metal hydroxide & Metallic oxihydroxides** | Gibbsite $Al(OH)_3$<br>Brucite $Mg(OH)_2$<br>Goethite (FeOOH) | Dehydration around exchangeable cations is completed at 150°C (gibbsite, goethite).<br>Loss of crystal-lattice water begins at 150-250°C (gibbsite, brucite, goethite). |
| **Carbonate minerals** | Calcite $CaCO_3$ | $CO_2$ evolves between 800 and 850°C. |
| | Dolomite $CaMg(CO_3)_2$ | $CO_2$ evolves between 700 and 750°C. |
| | Siderite ($FeCO_3$), Magnesite ($MgCO_3$), Rhodochrosite ($MnCO_3$) | $CO_2$ evolves between 425 and 520°C. |
| **Hydroxy-interlayered minerals** | HIV (hydroxy-interlayered vermiculite)<br>HIS (hydroxyl-interlayered smectite) | Dehydroxylation between 370 and 500°C. |
| **Elemental C** | Charcoal | Thermal decomposition in 2 phases: a small amount 105-350°C and a broad peak 450-550°C. |
| **Hydrated salts** | Gypsum $CaSO_4.2H_2O$ | 1.5 $H_2O$ lost at 128°C and the remaining $H_2O$ at 163°C. |
| | Epsom salts $MgSO_4.7H_20$ | 6 $H_2O$ lost at 150°C and the remaining $H_2O$ at 200°C. |
| | $CaCl_2.6H_2O$ | 4 $H_2O$ lost at 30°C and the remaining $H_2O$ at 200°C. |
| **Other salts** | $NaHCO_3$ | Decomposes to NaOH and $CO_2$ at 270°C. |

## 5.2.2. Soil Organic Carbon (SOC)

### *5.2.2.1. Definition of SOC*

The focus of this study is on SOC, the main component of SOM. C is present in the soil in two forms. The C present in SOM and elemental C (coal, charcoal, and graphite) together form the organic carbon (OC). Inorganic carbon (IC) is composed mainly of carbonate minerals, such as calcite and dolomite (Nelson & Sommers, 1982). Together they make up tot the total carbon (TC) content of the soil.

### *5.2.2.2. Measuring SOC*

Various techniques to measure SOC will now be discussed in greater detail. The choice of which C assessment method to use is a critical decision which affects the estimation of soil organic C stocks and their change over time (Bryre & Slaton, 2003). Each of the methods described has advantages and limitations and the method selected should be carefully assessed in terms of the purpose of analyzing soils. The difficulty is that modifications in analytical methodology, operational range limits and laboratory performance are rarely recognised and quantified in C accounting efforts (De Vos et al., 2007).

**Wet oxidation & measuring of Cr (type Walkley & Black)**

This method implies wet oxidation of OC in an acid dichromate solution followed by back titration of the remaining dichromate with ferrous ammonium sulphate and a suitable indicator, or by photometric determination of $Cr^{III}$. The most commonly used method was first described by Walkley & Black (WB) (1934), where OC is oxidized solely by the action of acid dichromate, heated by the exothermic mixing of aquaceous dichromate and concentrated sulphuric acid. Oxidation of OC can be improved by supplementary heating (Schollenberger, 1945). Positive errors can be expected in soils under highly reduced conditions with high concentrations of $Fe^{2+}$ and salt affected soils. Small negative errors can occur within manganiferous soils containing $MnO_2$ (Nelson & Sommers, 1982). Elemental C, e.g. charcoal, is to a large extent excluded (Metson et al., 1979) but it can influence the recovery considerably depending on the WB method variant (Bremner & Jenkinson, 1960) and the particle size, origin and nature of the charred material (Skjemstad & Taylor, 1999). Despite several difficulties and inaccuracies, this method is widely used because it requires a minimum of equipment, can be adapted to handle large numbers of samples, and it is suitable for comparative work on similar soils (Tiessen & Moir, 1993). Several studies have demonstrated the necessity to determine soil-specific correction factors for WB data sets when these data are compared with other standardized SOC assessments. These different correction factors result from differences in vegetation (Diaz-Zorita, 1999), management system (Hussain & Olson, 2000), soil type and texture (Allison, 1960; De Vos et al., 2007), depth (Drover & Manner, 1975) and WB method (De Vos et al., 2007).

**Wet oxidation and determination of $CO_2$**

After wet oxidation of OC in an acid dichromate solution, the evolved $CO_2$ is collected and determined. This can involve a combustion train and gravimetric or titrimetric $CO_2$ determination, or using the Van Slyke-Neil apparatus and manometric $CO_2$ determination. If no pre-treatment of calcareous soils is used, carbonates dissolved by the acid medium will be included in the $CO_2$ determination to give a measure of total C (Nelson & Sommers, 1982).

### Dry oxidation

This method involves oxidation of OC by heating the soil to at least 900°C in a flow of oxygen-containing gas that is free from $CO_2$. The amount of $CO_2$ released is then measured by titrimetry, gravimetry, conductometry, gas chromatograpy or using an infrared detection method, depending on the apparatus used. At high furnace temperatures, carbonates will also decompose, giving a measure of total C (Nelson & Sommers, 1982; ISO, 1995).

### Reflectance spectroscopy

Spectral signatures of materials are defined by their reflectance or absorbance, as a function of wavelength in the electromagnetic spectrum. Under controlled conditions, the signatures result from electronic transitions of atoms and vibrational stretching and bending of structural groups of atoms that form molecules or crystals (Sheperd & Walsh, 2002). Diffuse reflectance spectroscopy is routinely used for the rapid non-destructive characterization of a wide range of materials (Davies & Giangiacomo, 2000). Recent research has demonstrated the ability of reflectance spectroscopy to provide non-destructive rapid prediction of soil physical, chemical and biological properties in the laboratory (Ben-Dor & Banin, 1995; Janik et al., 1998; Reeves et al., 2002; Sheperd & Walsh, 2002). Near and mid infrared reflectance (NIR and MIR) spectroscopic determinations require the development of calibrations that relate the spectral information to the analysis in question, i.e. C content in soils. A spectral library can thus be built. Advantages of this technique are that it is non-destructive and rapid, that several soil properties can be determined simultaneously and that it is suitable for large-scale research, for example with the help of remote sensing techniques (Shepherd & Walsh, 2002).

### Conversion between SOC and SOM

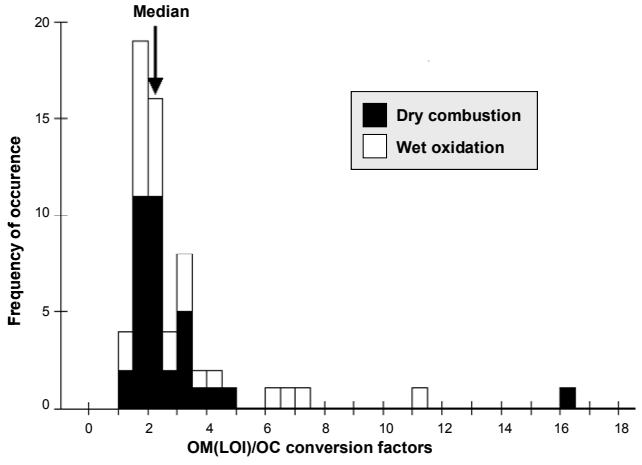



***Figure 5.2 Frequency distribution of organic matter to organic carbon conversion factors. (Sutherland, 1998).***

The relationship between organic matter and organic carbon can be represented by a factor OC/OM. This conversion factor for plant material is set by default at 0.5 and for litter at 0.37 (IPCC, 2006). Conversion factors that relate SOC to SOM (measured with LOI) are however highly variable. The traditional factor of 0.58 (Schulze, 1849; Wolff, 1864) is considered too high by many authors (Read & Ridgell, 1922; Jain et al., 1997; Sutherland, 1998) and may lead to errors as large as 50% for some material types (Huntington et al., 1989). This may lead to overestimation of regional C stocks by as much as 15% (Bhatti & Bauer, 2002). Values of the conversion factor of 0.53 for surface soils and 0.40 for subsoils would be more satisfactory (Broadbent 1953). Measured OC/OM ratios can vary with soil depth, parent material and vegetation type (Read & Ridgell, 1922; Huntington et al., 1989) and organic matter chemistry (Bhatti & Bauer, 2002). A summary of 61 reported relationships between OC determined by dry combustion and wet oxidation methods and LOI (OM) indicate that the

mean OM/OC conversion factor is 2.96 (OC/OM=0.34) and the median is 2.13 (OC/OM=0.47) (Figure 5.2) (Sutherland, 1998).

However many authors state clearly that their regression equations are only valid for specific data sets with respect to the sampled soil strata, soil types, land use and regional conditions and could not be applied to different soils without verification (Konen et al., 2002). The use of an intercept in the regression equation may express the residual effect of other components (as discussed in Table 5.2) (De Vos et al., 2005b). When an intercept is added to the model, slope parameters presented in the literature vary between 0.405 and 0.960 (Sutherland, 1998).
Therefore, it is strongly recommended to develop local regressions based on an intercept model and to calibrate individual equations for each textural group (De Vos et al., 2005b).
LOI provides a precision comparable to a TOC analyzer, although the latter is able to quantify low OC contents more reliably. Operating costs of LOI versus total analyser methods are estimated 1:12 and time consumption 1:2.3 (De Vos et al., 2005b). If LOI and OC are measured and equations are developed for a subset of samples, LOI provides an accurate, cost effective and simple technique for the routine estimation of OC (Bhatti & Bauer, 2002).

### 5.2.3. Soil bulk density (BD)

Soil bulk density (BD) is the mass of an oven dry sample of undisturbed soil per unit volume (Salifu et al., 1999). BD is an important physical property which is needed for mass to volume or area conversions of soil properties; therefore it is indispensable for the assessment of soil C stocks and nutrient pools (De Vos et al., 2005a; Tamminen & Starr, 1994) and it is the mandatory measuring unit for soil C assessment in CDM A/R (Clean Development Mechanism Aforestation/Reforestation) accounting (UNFCCC, 2007).

The determination of the soil BD usually implies drying and weighing a soil sample, the volume of which is known (core method) or must be determined (clod method and excavation method). In the core method, a known volume of soil is sampled using a metal ring, dried and weighed. Excavation methods were developed in recent years for gravely or loose material. An unknown volume of soil is removed, weighed, and replaced by the same volume of water, which can be measured. The BD of clods, or peds, can be calculated from their mass and volume. The volume may be determined by coating a clod of known mass with a water-repellent substance and by weighing it first in air, then again while immersed in a liquid of known density, making use of Archimedes' principle. A different principle is employed with the radiation method, which can be used in situ. Transmitted or scattered gamma radiation is measured; and with suitable calibration, the density of the combined gaseous-liquid-solid components of a soil mass is determined (Blake & Hartge, 1986). All the methods have advantages and disadvantages according to the samples that are available and the sampling method.

Unfortunately, BD is not always determined in routine soil surveys, as the procedures are tedious, labour-intensive, time-consuming and expensive (Harrisson & Bocock, 1981; Boucneau et al., 1998; Kaur et al., 2002). According to Vågen et al. (2005), the biggest constraint to current estimates of SOC stocks in Sub-Saharan Africa is the lack of BD data. To overcome this problem, pedotransfer functions (PTFs) are frequently used. A PTF translates basic soil data into another soil property, in this case BD. BD has been found to be determined predominantly by OC or OM and texture. These properties are often available in

soil survey campaigns. Therefore many attempts have been made to estimate soil BD through some PTFs based on soil OC or OM and texture data (Alexander, 1980; Rawls, 1983; Huntington et al., 1989; Tomasella & Hodnett, 1998; Bernoux et al., 1998; Manrique & Jones, 1991; Kaur et al., 2002). In many cases, especially in uncultivated soils, OM has a dominant effect on BD and can be used alone as a good predictor of BD (Jeffrey, 1970; De Vos et al., 2005a). Only in soils where OM is a minor component, soil texture plays a major role in controlling BD (Alexander, 1980; Huntington et al., 1989; Manrique & Jones, 1991). BD has also been found to vary with depth (Harrisson & Bocock, 1981; Huntington et al., 1989; Leonavičiutė, 2000), soil group (Alexander, 1980; Manrique & Jones, 1991; Salifu et al., 1999), land use and vegetation (Harrisson & Bocock, 1981). It has been advised to calibrate and validate specific PTFs on a regional basis to enhance the accuracy and precision of BD prediction (Alexander, 1980; Salifu et al., 1999; Kaur et al., 2002; De Vos et al., 2005a).

### 5.2.4. Vertical evolution of SOC

SOC is known to decrease with soil depth (Arrouays & Pelissier, 1994; Jobbágy & Jackson, 2000; Yang et al., 2007). The vertical SOC distribution is mainly determined by vegetation and secondly by climate (Jobbágy & Jackson, 2000; Yang et al., 2007). The relative distribution of SOC in the first meter of soil is deepest in shrublands, intermediate in grasslands and shallowest in forests (Jobbágy & Jackson, 2000). Root distributions affect the vertical placement of C in the soil, and above-and belowground allocation affects the relative amount of C that eventually falls onto the soil surface from shoots. In a global review of root distributions, grasses had the shallowest root profiles, trees were intermediate, and shrubs had the deepest profiles (Jackson et al., 1996). The reason the relative C distribution is deeper in grasslands is explained by higher relative aboveground allocation for trees than for grasses and shrubs. The quality of C inputs, often characterized by lignin content, is another important control of decomposition rates and may contribute to observed differences for forests and grasslands. Woody aboveground inputs and relatively low decomposability in forests could increase SOC storage in surface soils compared to grasslands (Jobbágy & Jackson, 2000).
The relative distribution of SOC with depth is slightly correlated with climate, SOC distributing more deeply as precipitation decreases and temperature increases. The association with precipitation can be largely accounted for by the replacement of vegetation types along precipitation gradients. The temperature pattern agrees with the observation that the ratio of litter to mineral soil C decreases from temperate to tropical forests (Jenny, 1950) and suggests that mean annual air temperature may have a proportionally higher effect on the decomposition of shallow SOC than on deep SOC (Jobbágy & Jackson, 2000).

Several functions have been used to relate cumulative or non-cumulative SOC contents or SOC densities with depth. Simple, flexible functions are preferred that capture the relative slope of depth profiles (i.e. independently of total SOC content) with a single parameter. Logarithmic, exponential, polynomial and other models have been proposed in literature (Jobbágy & Jackson, 2000).

# 5.3 Methodology

Keeping this literature review in mind, solutions were found for the problems stated in the introduction:

1. SOC of a subset of samples from the 2005 dataset was measured using dry oxidation, and a regression equation between SOM and SOC was developed;
2. Pedotransfer functions which estimate BD based on other soil properties were developed from the Bennett et al. (1979) dataset and used in the datasets of ITCRP (1981) and Ngatunga (2001);
3. Equations describing the vertical C evolution could be established using the datasets of Bennett et al., (1979), ITCRP (1981) and Ngatunga (2001). However, since these equations depend on land use, the Bennett dataset could not be used to make this distinction and only the two others were used. The vertical C distribution for the whole profile was calculated for the new dataset;
4. SOC stocks were calculated for all datasets using Equation 5.1 as well as general statistics (mean, median, SD, minimum, maximum).

## 5.3.1. Measuring LOI and deriving SOC

The samples of 2005 were tested for SOM with the method of loss-on-ignition as follows. Samples were dried at 105°C, crushed, sieved with a 2 mm sieve and thoroughly mixed. The mass of the 0-2mm and > 2mm fractions was determined with a precision of 1g. The 0-2mm fraction was dried again just before measuring loss-on-ignition (LOI). For most samples a drying temperature of 105°C (24 hrs) was chosen. One of the main errors resulting from additional weight loss from constituents other than SOM (described in Table 5.2) which can be expected in southeastern Tanzania, is the loss if hygroscopic and intercrystalline water in swelling clays of Vertisols. Therefore all Vertisol samples are preheated for 2 hours at 200°C. Organic matter content was determined on a 3g subsample of the 0-2 mm fraction with the LOI method (3 hrs combustion at 550°C). A temperature of 550°C minimizes the amount of weight loss due to carbonate minerals.

SOC levels were determined for a subset of 100 samples, which were selected from most types of soil and land-use in the study area. Total C content of these samples was determined using dry combustion at 1000°C with an elementar VarioMax CN analyzer, according to ISO 10694 (ISO, 1995). Since none of the soils in the subset contained carbonates (inorganic C), total C is in this case equal to total organic carbon, including small amounts of elemental C from charcoal.

Error variances for SOM (from LOI) and SOC (from dry combustion) based on replicate samples were calculated as follows:

$$\sigma_x^2 = \frac{\sum_{i=1}^{n} (x_i' - x_i'')^2}{2n} \qquad \textit{Equation 5.2}$$

where $\sigma_x^2$ is the error variance of variable x, $x_i$' and $x_i$" are two replicates of $x_i$ and n is the number of samples. $\sigma_{SOM}^2$ and $\sigma_{SOC}^2$ were estimated at 0.012 (n=35) and 0.040 (n=10) respectively.

Regression equations relating SOC to SOM were developed in SPSS with an intercept for different subsets from the database. However, due to the measurement error of SOM, the regression coefficient is not the best estimator of the slope parameter when deriving SOC from SOM (Lettens et al., 2007; Webster, 1997). Webster (1997) advises the use of structural analysis to correct the regression coefficients by taking into account the observed error of SOM. However, Lettens et al. (2007) suggest taking into account the relative importance of the error in SOM to the error in SOC by estimating the factor

$$\lambda = \sigma^2_{SOM} / \sigma^2_{SOC} \qquad \textbf{Equation 5.3}$$

where $\sigma^2_{SOM}$ and $\sigma^2_{SOC}$ are the error variances of SOM and SOC. It appeared that when λ was less than 0.5, the regression could be used to estimate SOC from SOM (Lettens et al., 2007). The factor λ was estimated at 0.3, thus the developed regression equations could be used to deduct SOC from SOM in all other samples taken in the 2005 survey.

## 5.3.2. Estimation of bulk densities

Since the dataset of Bennett et al. (1979) contains data on texture, SOC content (with WB) and bulk densities, it can be used to create pedotransfer functions. First general statistics of these soil properties were calculated in SPSS. De Vos et al. (2005a) described 5 model types of pedotransfer functions which were most found in literature (Table 5.3). These types were tested against the 153 horizon descriptions.

***Table 5.3 Five model equations for pedotransfer functions (from De Vos et al., 2005a), with: BD = bulk density (g/cm$^{-3}$), OC = SOC content (%), Sand = 50 µm-2mm fraction (%), Clay = 0-2 µm fraction (%), Depth = sampling depth (cm).***

| Model type | Model equation |
|---|---|
| A | $BD = \alpha + \beta_1 \log_{10}(OC) + \beta_2 \log_{10}(Sand) + \beta_3 \log_{10}(Clay) + \beta_4 \log_{10}(Depth)$ |
| B | $BD = \alpha + \beta_1 (OC)^{1/2} + \beta_2 (Sand)^{1/2} + \beta_3 (Clay)^{1/2} + \beta_4 (Depth)^{1/2}$ |
| C | $BD = (\alpha + \beta_1 OC + \beta_2 Sand + \beta_3 Clay + \beta_4 Depth)^{-1}$ |
| D | $\ln(BD) = \alpha + \beta_1 \ln(OC) + \beta_2 [\ln(OC)]^2 + \beta_3 \ln(Sand) + \beta_4 \ln(Clay) + \beta_5 \ln(Depth)$ |
| E | $\ln(BD) = \alpha + \beta_1 OC + \beta_2 Sand + \beta_3 Clay + \beta_4 Depth$ |

First, 100 randomly chosen points from the 153 horizons were chosen for calibration. Multiple regression was performed on all five model types, using three variable groups separately: (i) group O using an organic (OC) variable only, (ii) group T using texture variables (Clay and Sand) only and (iii) group A using all variables including sampling depth, if they significantly ($p<0.05$) contributed to the stepwise regression model. The variable groups O, T and A applied on the 5 model types lead to 15 model PTFs coded AO, AT, AA ,BO … EA. These models were evaluated to assess the relative importance of their predictor variables. The (stepwise) linear regression models were created using SPSS for Windows (version 11.5.0).

Validation of the models was done using the 53 remaining points. Graphs show the relationship between observed and estimated bulk densities. The calculation of validation indices was used for further evaluation of the prediction models (De Vos et al., 2005).

These are defined as:
The mean predicted error (MPE)

$$MPE = \frac{1}{n}\sum_{i=1}^{n}(\hat{\rho}_{b,i} - \rho_{b,i}) \qquad \textbf{Equation 5.4}$$

The standard deviation of the prediction error (SDPE)

$$SDPE = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}((\hat{\rho}_{b,i} - \rho_{b,i}) - MPE)^2} \qquad \textbf{Equation 5.5}$$

The root mean square prediction error (RMSPE)

$$RMSPE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{\rho}_{b,i} - \rho_{b,i})^2} \qquad \textbf{Equation 5.6}$$

And the prediction coefficient of determination ($R_p^2$)

$$R_p^2 = \frac{[\mathrm{cov}(\rho_{b,i}, \hat{\rho}_{b,i})]^2}{\mathrm{var}(\rho_{b,i}).\mathrm{var}(\hat{\rho}_{b,i})} \qquad \textbf{Equation 5.7}$$

where $\rho_{b,i}$ and $\hat{\rho}_{b,i}$ are the observed and predicted bulk density values respectively, n the number of observations, and var and cov the variance and the covariance function respectively.

## 5.3.3. Calculation of vertical SOC distribution

The datasets of the ITCRP (1981) and Ngatunga (2001) provided complete soil profile descriptions with SOC concentrations measured for each horizon, and information about soil type and land use.
Since no bulk densities were available for these data, evolution of C content (%) instead of C densities was chosen. In order to compare the relative vertical distribution of SOC independently of total SOC content, relative SOC contents were calculated by dividing the SOC content of the horizon by the average SOC content of the profile, as proposed by Jobbágy & Jackson (2000).
The curves of C profiles were fitted using different equations drawn from the literature (Jobbágy & Jackson, 2000; Hillinski, 2001):

1. $\ln(SOC_{rel}) = a + b * depth$ **Equation 5.8**
2. $\ln(SOC_{rel}) = a + b * \ln(depth)$ **Equation 5.9**
3. $SOC_{rel} = a + b * e^{c*depth}$ **Equation 5.10**

where $SOC_{rel}$ is the relative SOC content (in %), depth is the depth of the sample (in cm) and a, b and c are parameters that have to be estimated. These models were fitted by minimizing the coefficient of determination.

Profiles were grouped according to their soil type (major soil group of WRB (FAO, 2006)) and land use. Land use classes, which could be distinguished in the dataset, are: (i) grassland, (ii) woodland, (iii) bushland, (iv) cashew fields, (v) cashew fields intercropped with food crops and (vi) crops without trees. Woodland and bushland were distinguished based on the descriptions of the authors, but the boundary is not clear and many intermediate vegetation types exist.

Confidence intervals (95%) for the parameters were calculated in order to distinguish between groups of soil type and land use. When confidence intervals did not overlap, the regressions were considered significantly different. Statistics were performed using SPSS for Windows (version 11.5.0).

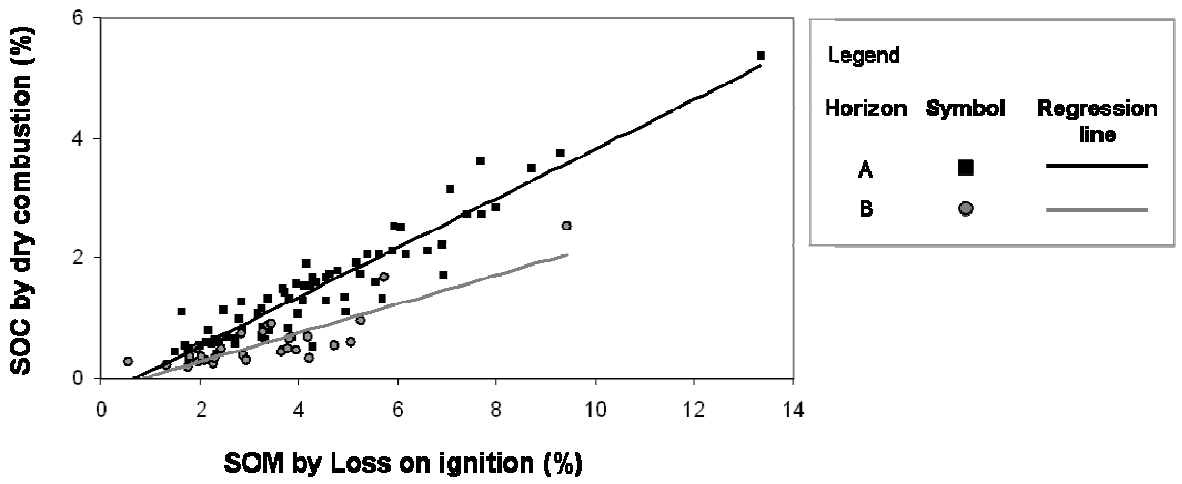
### 5.3.4. Calculation of SOC stocks

SOC densities were calculated until 1m depth for every profile of the different datasets using Equation 5.1. Mean and median values of the different datasets were calculated. It was checked whether the different datasets eventually gave different estimations of SOC and whether they were consistent with values from the literature.

## 5.4 Results

### 5.4.1. Deriving SOC from SOM

Linear regression between all points measured with LOI and total combustion resulted in following relationship: SOC = -0.400 +0.403 SOM. Although this formula explains 80% of the variation ($R^2$ = 0.807), on the scatter plot of Figure 5.3 it can be observed that data are spread in different directions.




| Regression | Regression equation | Interval intercept | Interval slope | Coefficient determination |
|---|---|---|---|---|
| A-horizon: | SOC = -0.284 + 0.411 SOM | -0.468 → -0.100 | 0.373 → 0.448 | $R^2$ = 0.878 |
| B-horizon: | SOC = -0.202 + 0.240 SOM | -0.411 → -0.202 | 0.183 → 0.240 | $R^2$ = 0.728 |

***Figure 5.3 Regression between SOC (measured with dry combustion) and SOM (measured with LOI) for the A and B horizons (n=100).***

After dividing the dataset according to soil type, vegetation type and depth, the only significant distinction could be made between the A (measured at 0-5 cm) and B horizons (measured at 40-45 cm). Figure 5.3, presenting the regression parameters for both horizons with their 95% confidence intervals, proves that

the slope parameters of A and B horizon are significantly different. The intercepts are significantly different from zero but not significantly different from each other.

## 5.4.2. Estimation of bulk densities

Table 5.4 gives some general statistics on soil properties of the 154 soil samples from the 40 profiles by Bennett et al. (1979). Samples were taken in each horizon of the full profile (to 1m depth or more). OC content was generally low (mean value of 0.58% OC) but very variable, with a maximum of 2.96%. Soil texture varied between sand and heavy clay. Bulk densities varied between 1.05 and 1.59 g $cm^{-3}$, which is common for mineral soils.

***Table 5.4 General properties of the dataset by Bennett et al. (1979).***

| Soil properties | N | Mean | Minimum | Maximum | Standard Deviation |
|---|---|---|---|---|---|
| **OC (%) by WB** | 154 | 0.58 | 0.06 | 2.96 | 0.54 |
| **Clay (%)** | 154 | 34 | 2 | 92 | 25 |
| **Sand (%)** | 154 | 56 | 1 | 94 | 28 |
| **BD (g $cm^{-3}$)** | 154 | 1.28 | 1.05 | 1.59 | 0.12 |

Using a calibration dataset of 100 horizons, regression functions for the different models were developed (Table 5.5). Coefficients of determination for the models using OC only varied between 0.18 and 0.22 while models based on texture only had $R^2$ between 0.70 and 0.73, hereby indicating that texture accounted for more than 3 times as much variability as C content. Stepwise multiple regressions with all variables did not alter the texture models of C and E and enhanced the explained variance of the texture models A and D with no more than 0.022. The best 2 models are Aa and Da; with a regression based only on clay content and depth. Models C and E generally performed worst.

A validation dataset of 54 samples was used to test the performance of the models. The Mean Predicted error (MPE) evaluates the bias of a PTF. The MPE is almost zero for models A, B and D. The most negative bias is observed in models Ct and Et and a positive bias in model Ea. The SDPE (standard deviation of the prediction error) measures the random variation of the predictions after correction for the global bias. It is affected by four sources of uncertainty: the limited precision of the model, local deviations of the model from the real situation, the inherent variability of the property measured and the measurement error. It performs badly for all models based on organic C only. The RMSPE is a measure of the overall error of the prediction. It is the square root of the MSPE, which evaluates the total prediction quality, since for n being large, the MSPE equals the sum of $MPE^2$ (accuracy error) and $SDPE^2$ (precision error). It performs worst for models based only on C content and best for the stepwise regression models, especially Aa and Da. The ratios $MPE^2/MSPE$ and $SDPE^2/MSPE$ give the relative contribution of accuracy and precision to the total prediction error. For most models the error is mainly error in precision. The contribution of the accuracy error is only noticeable in models Ct and Et. The

Pearson correlation coefficient (r) is a measure for the linearity between observed and predicted values. The highest value is reached for models Aa and Da.

***Table 5.5 Calibration and validation parameters of the different models of pedotransfer functions calculated on the dataset of Bennett et al. (1979), with: OC = SOC content (%), Sand = 50 µm-2mm fraction (%), Clay = 0-2 µm fraction (%), Depth = sampling depth (cm), Significance codes: 0 -***- 0.001-**- 0.01-*- 0.05 -°- 0.1; MPE = mean predicted error, SDPE = standard deviation of the prediction error, RMSPE = root mean square prediction error, $R_p^2$ = prediction coefficient of determination.***

| Model | Calibration | | | | | | | Validation | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Intercept | OC | Sand | Clay | Depth | $R^2$ | Adj. $R^2$ | MPE | SDPE | RMSPE | $R_p^2$ |
| **$A_o$** | 1.229*** | -0.126*** | | | | 0.183 | 0.175 | 0.0138 | 0.111 | 0.111 | 0.518 |
| **$A_t$** | 1.597*** | | 0.002 | -0.236*** | | 0.734 | 0.729 | 0.0005 | 0.067 | 0.067 | 0.847 |
| **$A_a$** | 1.575*** | | | -0.262*** | 0.039** | 0.756 | 0.751 | 0.0037 | 0.062 | 0.061 | 0.871 |
| **$B_o$** | 1.393*** | -0.163*** | | | | 0.209 | 0.201 | 0.0129 | 0.115 | 0.114 | 0.460 |
| **$B_t$** | 1.568*** | | -0.006 | -0.047*** | | 0.706 | 0.700 | -0.0014 | 0.073 | 0.072 | 0.826 |
| **$B_a$** | 1.520*** | -0.045* | | -0.039*** | | 0.718 | 0.712 | 0.0072 | 0.068 | 0.068 | 0.854 |
| **$C_o$** | 0.754*** | 0.058*** | | | | 0.217 | 0.209 | 0.0026 | 0.118 | 0.117 | 0.407 |
| **$C_t$** | 0.933*** | | -0.002*** | 0.000 | | 0.694 | 0.688 | -0.0554 | 0.079 | 0.096 | 0.804 |
| **$C_a$** | 0.905*** | | -0.002*** | | | 0.693 | 0.690 | -0.0116 | 0.077 | 0.078 | 0.804 |
| **$D_o$** | 0.204*** | -0.073*** | | | | 0.215 | 0.199 | 0.0057 | 0.119 | 0.118 | 0.382 |
| | | -0.018° | | | | | | | | | |
| **$D_t$** | 0.474*** | | 0.003 | -0.078*** | | 0.725 | 0.719 | -0.0026 | 0.067 | 0.067 | 0.845 |
| **$D_a$** | 0.471*** | | | -0.088*** | 0.014** | 0.747 | 0.742 | 0.0067 | 0.061 | 0.061 | 0.870 |
| **$E_o$** | 0.285*** | -0.074*** | | | | 0.214 | 0.206 | 0.0062 | 0.118 | 0.117 | 0.403 |
| **$E_t$** | 0.051 | | 0.003*** | 0.000 | | 0.697 | 0.691 | -0.0297 | 0.076 | 0.081 | 0.797 |
| **$E_a$** | 0.093*** | | 0.003*** | | | 0.696 | 0.693 | 0.0238 | 0.076 | 0.079 | 0.797 |

Differences in performance of the best models are reflected in the scatter plots (Figure 5.4). Although the mean predicted error of models Bt and Ba are comparable to those of Dt and Da respectively, the scatter plot indicates that model B has a tendency of underestimation in the extremes, and overestimation in the middle. The logarithmic functions of models A and D seem to overcome this problem and these models perform better. Indeed, several researchers (e.g. Loagnes & Corwin, 1996) have observed that it is not rare to find 2 different empirical methods giving the same mean error values for quite different representation of hydrological properties. It had therefore been recommended (ASCE, 1993) that both visual (graphical) and statistical comparisons between the observed and the estimated values should be used for comparing distribution patterns, identifying systematic errors (in the form of over and under predictions), and characterising spatial variations between field observations and model predictions.

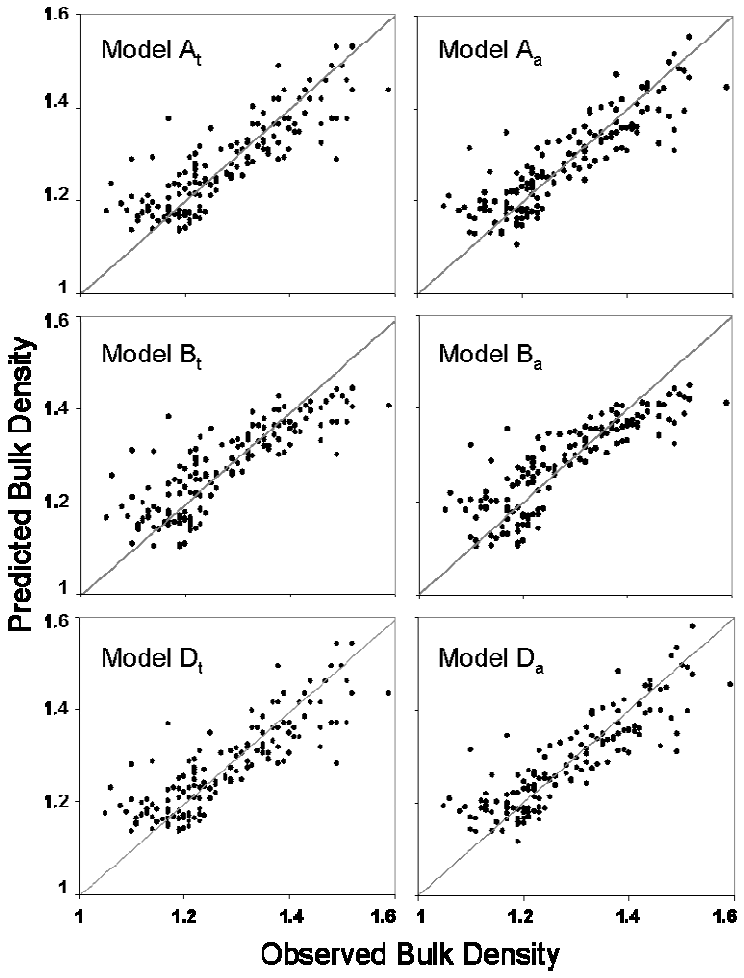



***Figure 5.4 Scatter plots of the predicted versus observed bulk densities based on the best 6 models.***

It can be concluded that the best models for estimating bulk densities are logarithmic functions based on clay content and depth. These models are:

$BD = 1.575 - 0.262 \log_{10}(clay) + 0.039 \log_{10}(depth)$ with $R^2 = 0.76$ ***Equation 5.11***

$Ln\ BD = 0.471 - 0.088 \ln(clay) + 0.747 \ln(depth)$ with $R^2 = 0.75$. ***Equation 5.12***

Since both models perform equally well, the first one is preferred since the response is not transformed.

## 5.4.3. Vertical distribution of SOC

The three proposed models were tested against the whole dataset and regression parameters were calculated with following results:

1. $\ln(SOC_{rel}) = 0.333 - 1.186 * depth$ $R^2 = 0.380$ ***Equation 5.13***
2. $\ln(SOC_{rel}) = -0.579 - 0.380 * \ln(depth)$ $R^2 = 0.379$ ***Equation 5.14***
3. $SOC_{rel} = 0.560 + 1.189 * e^{-3.505*depth}$ $R^2 = 0.405$ ***Equation 5.15***

where $SOC_{rel}$ is the relative SOC content (in %) and depth is the depth of the sample (in cm).
Equation 5.15 has the lowest coefficient of determination and is therefore the best option. Although Equation 5.13 was used in the scope of this study for ease of use, it is advised to use the better fitting model in the future.

Since the SOC content is already known at 0 and 40 cm, it can now be calculated for any depth in the profile as follows:

$\ln(SOC_{rel}) = a + b * depth$

and $SOC_{rel,e} = SOC_e/SOC_{average}$ ; $SOC_{rel,m} = SOC_m/SOC_{average}$

→ $\ln(SOC_{rel,e}) - \ln(SOC_{rel,m}) = b * (depth_e - depth_m)$

$$\rightarrow \ln\left(\frac{SOC_e}{SOC_{average}} * \frac{SOC_{average}}{SOC_m}\right) = b * (depth_e - depth_m)$$

→ $\ln(SOC_e) = \ln(SOC_m) + b * (depth_e - depth_m)$

or $\Delta \ln SOC = b * \Delta depth$ ***Equation 5.16***

Where $SOC_{rel,e}$ and $SOC_{rel,m}$ stand for the estimated and measured relative carbon content respectively, $SOC_e$ and $SOC_m$ are the estimated and measured SOC contents (%), $SOC_{average}$ is the average SOC content of the whole profile, $depth_e$ and $depth_m$ are the sample depths of the estimated and measured carbon contents (in cm) and Δ stands for difference between estimated and measured variables.
As can be seen in Equation 5.16, the average SOC stock and the intercept (a) are of no further importance when the SOC stock at one depth is already known.

Now that the model has been chosen, Equation 5.8 is recalculated for different groups of soil type and land use. The 95% confidence intervals of slope parameters were calculated to determine significant differences between soil types and land uses. It revealed no differences in slope parameter between soil types, but it showed that the vertical distribution of grassland and crops is significantly different from woodland and bushland. Cashew and intercropped cashew fields had an intermediate vertical distribution. Slope parameters were recalculated for the 3 groups. Although confidence intervals are wide and coefficients of determination are rather low, it was possible to distinguish the 3 groups of land uses and set up their regression equations (Table 5.6). The regression equations were used to extrapolate SOC contents to 1m depth in the 2005 dataset.

***Table 5.6 Model of the vertical distribution with 95% confidence interval of the slope parameter and coefficient of determination for the regression of Equation 5.8, developed for the 3 different land use classes (SOC = soil organic content in %, depth = depth of sample in cm, Δ SOC = SOC difference between two depths Δ depth).***

| Land Use | Vertical distribution model | Confidence Interval of slope parameter | | $R^2$ | n |
|---|---|---|---|---|---|
| **Grassland & crops** | Δ ln SOC = -48.7 Δ depth | -65.0 | -32.5 | 0.257 | 194 |
| **Cashew & intercrop** | Δ ln SOC = -81.5 Δ depth | -81.5 | -62.3 | 0.407 | 321 |
| **Woodland & shrubland** | Δ ln SOC = -93.4 Δ depth | -93.4 | -72.2 | 0.414 | 337 |

### 5.4.4. Calculation of total SOC stocks

Having filled all the gaps in the different datasets, it is now possible to calculate the SOC density to 1m depth of every profile using Equation 5.1. The general results are presented in Table 5.7.

***Table 5.7 Summary of SOC densities ($Mg.ha^{-1}$, 1m depth) for 617 soil profiles by different authors.***

| Author | n | Mean | Median | Std. Deviation | Minimum | Maximum |
|---|---|---|---|---|---|---|
| **Bennett et al. (1979)** | 40 | 69.5 | 45.2 | 50.6 | 18.8 | 209.6 |
| **ITCRP (1981)** | 211 | 96.7 | 86.9 | 54.4 | 15.1 | 273.0 |
| **Ngatunga (2001)** | 30 | 51.4 | 50.3 | 20.5 | 19.5 | 96.3 |
| **New dataset** | 336 | 61.6 | 37.1 | 62.4 | 0.4 | 426.7 |
| **Total** | 617 | 73.6 | 55.5 | 60.0 | 0.4 | 426.7 |

## 5.5 Discussion

### 5.5.1. OC/OM regression

Two different regressions between SOC and SOM were proposed for the A and B horizon.

The intercept of the two lines was not significantly different. It represents the overestimation of SOM in LOI because of weight loss by other soil constituents and has the same value for every sample, independent of the organic carbon level. In the soils of the study area, this additional weight loss could be attributed to the desorption of clay water from kaolinite, removal of hygroscopic water of vermiculite and illite, dehydration around gibbsite and goethite, dehydroxylation of crystal-lattice water from gibbsite and goethite and dehydroxylation of HIV and HIS. These minerals are very common in the old soils found in the area.

A significant different slope parameter was obtained for the A and B horizons: respectively 0.411 and 0.240. The first value, for the A horizon, is close to conversion factors found in literature (Sutherland, 1998). Broadbent (1953) already proposed that conversion factors for surface soil should be higher than those for subsoils. However, the slope factor for the subsoil is much lower than generally described in the literature. Santisteban et al (2004) found very low slope parameters in regression equation based on the intercept model, for gypsum-rich, organic-poor facies. In this case the low slope parameter may again be related to weight loss of clay minerals. An error on the slope factor would assume that the additional inorganic weight loss depends on the organic carbon content: more weight loss is observed at higher organic carbon levels. This could be attributed to a relationship between clay content and organic carbon level, especially in the subsoil. This could not be verified since texture analysis was not conducted on the samples used for the regression equation. De Vos et al. (2005) recommend calibration of regression equations for each textural group, or, if clay content is available, the use of a bivariate regression model.
In future studies it is advised to preheat all for 2 hours at 200°C to reduce the errors made by LOI and to reduce the intercepts.

Since λ, or the relative importance of the error variance of SOM versus SOC, was below 0.5, the regression equations can now be used to convert SOM values of the whole dataset taken in 2005 to SOC values. For a few very small SOM values, subtracting the intercept results in a negative SOC content. For these soils the weight loss by other soil constituents is overestimated and it is not possible to estimate the C content, which is however very low. In order to maintain these samples in statistical analyses, their SOC content is set at zero.

## 5.5.2. Pedotransferfunctions

Equations 5.8 and 5.9 were the best PTFs for the estimation of BD. They depended in the first place on the clay content, and secondly on the depth of the sample. They did not depend directly on the OC content. In soils rich in OC, the aggregation effect of organic matter causes the lower BD. In our soils OC contents are generally very low. However, aggregation can be caused by other factors. A typical feature of these old soils is the presence of negatively charged clay minerals, which combine with positively charged sesquioxides to form strong micro-aggregates of silt ('pseudo-silt') or sand ('pseudo-sand') size (Driessen & Dudal, 1991). In clay-rich soils such well developed micro-structures could lower the BD more than the small effect of the low OC content. Analogously, clay content was the most important predictor for BD in Ferralsols, Acrisols and Lixisols of Brasilia (Benites et al., 2007).
Lower BDs higher in the profile are probably the result of the combined effect of higher OM contents and more decompactation by biotic activity of soil fauna and roots in the topsoil versus the subsoil.

The fact that the functions do not depend on OC content, which distinguishes them from most relationships found in literature, emphasises the importance of making regional PTFs instead of relying on existing ones.

Equation 5.8 is now used to estimate bulk density values for all soil profiles in the datasets of ITCRP (1981) and Ngatunga (2001), since they already have information on texture and sampling depth. However the use of this formula for the estimation of bulk densities for future soil surveys is questionable. Although field sampling of bulk densities may be difficult, especially for deeper soil layers, the

determination in the laboratory is much easier than determination of soil texture. Measuring soil texture for the derivation of bulk densities does not bring any advantage.

### 5.5.3. Vertical distribution

The vertical distribution of SOC was significantly different between woodland versus grass- and cropland. In woodlands, bushlands the complex vegetation mixtures of bush- and woodland a high proportion of SOC is stored in the upper layers and the relative SOC distribution is shallow. This could be the result of the quality of C inputs. The relatively low decomposability in wood- and bushland could increase SOC storage in surface soils compared to grasslands, as suggested by Jobbágy & Jackson (2000). C from croplands is probably also easier decomposable. The deeper distribution of C in croplands could also be the result of soil disturbance during clearing and establishing of the field, although soil preparation and ploughing is limited in the study area.
Jobbágy & Jackson (2000) found a difference between forests (shallower distribution) and shrubland (deeper distribution) as a result of a higher aboveground allocation for trees than for shrubs. However the woodlands and bushlands of the study area and the many intermixed vegetation forms are expected to have comparable aboveground allocations, which explain why they had no different distribution.

Cashew fields have intermediate vertical SOC distributions, which are not significantly different from either crops or forests. The vegetation structure shows elements of the two other systems with a tree layer of cashew trees and sometimes an undergrowth of grass or crops.

An important factor influencing vertical SOC distribution is the presence of termites. Their activities cause homogenisation of the soil over considerable depths. However, they occur in all land uses thus their presence can not explain differences between land uses. The influence of termites on the distribution of SOC will be further discussed in Chapter 8.

### 5.5.4. Total SOC stocks

The mean value of the SOC stocks to 1m depth among all land uses and soils is 73.6 $Mg.ha^{-1}$. This number is very close to the values described in literature. Batjes (2004) found SOC stocks (0-1m) ranging between 72 and 75 $Mg.ha^{-1}$ in East Africa, while De Pauw et al. (1996) found ranges of SOC stocks (0-1m) between 79 and 82 $Mg.ha^{-1}$ in African regions with a growing period between 150 and 210 days (as occurring in the study area). It can be observed that the data range in every dataset is very large, indicating large difference in C storage capacities between soils. The reasons for these differences will be discussed in the next chapter. The variety of soils and land units is probably the reason for the differences in mean SOC values between the datasets. For example all profiles described by Ngatunga (2001) are situated in cashew plantations, which are expected to have lower than average SOC stocks, while almost half the profiles described by the ITCRP (1981) are taken in natural vegetation types.

# 5.6 Conclusions

This chapter sought practical solutions for measuring or estimating soil variables necessary for calculating SOC stocks (Equation 5.1). Following site-specific equations were presented (Table 5.8).

***Table 5.8 Site-specific equations for the calculation of SOC stocks.***

| Scope | Equations | Units |
|---|---|---|
| **Deriving SOC contents from SOM measured with LOI:** | *A-horizon*<br>SOC = -0.248 + 0.411 SOM<br>*B-horizon*<br>SOC = -0.202 + 0.240 SOM | SOM (%)<br>SOC (%) |
| **Estimating bulk densities:** | BD = 1.575 – 0.262 $\log_{10}$ (clay) + 0.039 $\log_{10}$ (depth) | BD ($g.cm^{-3}$)<br>Clay: 0-2 µm fraction (%)<br>Depth (cm) |
| **Vertical distribution of OC:** | *Grassland & crops*<br>Δ Ln SOC = -48.7 Δ depth<br>*Cashew & intercrop*<br>Δ Ln SOC = -81.5 Δ depth<br>*Woodland & shrubland*<br>Δ Ln SOC = -93.4 Δ depth | SOC (%)<br>Depth (cm)<br>Δ SOC: SOC difference between two depths (Δ depth) |

The mean SOC stock of the region, based on 617 soil profiles, was 73.6 $Mg.ha^{-1}$ (1m depth).

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# 6 Soils, Land Uses and SOC

# 6.1 Introduction

Global soil organic carbon (SOC) pools are difficult to estimate because of incomplete knowledge of specific soil properties at a global scale (Batjes, 1996), the high spatial variability of soil organic carbon (Bird et al., 2002) and the different effects of the factors controlling soil organic carbon (Côté et al., 2000). Thus, regional and national scale studies of soil organic carbon are necessary to refine global estimates (Bernoux et al., 2002). Both soil and land use data should be used in determining soil carbon stocks. While soil factors are important to explain carbon storage or pools over long periods of time, changes in vegetation or land use determine the changes in carbon sequestration over shorter periods (FAO, 2001). This chapter will discuss the relationship between SOC stocks under different soils and land uses of the study area. Once this relationship is known, a regional SOC map can be derived from the combination of a soil map and a land use map.

## 6.1.1. SOC mapping

Liebens & Van Molle (2003) compared different methods used in worldwide literature to estimate regional carbon stocks. Kern (1994) derived SOC contents from a major land resources map and a soil map of the world. Howard et al. (1995) mapped the geographical distribution of SOC in Great Britain in 10 km x 10 km blocks. Their estimates were based on the dominant soil series and land cover type for 1 km x 1 km blocks, the bulk density for the soil series and the SOC content for each soil series/land cover combination. In a Brazilian study a soil map was reclassified into 6 general soil types and intersected with a generalized vegetation map. For each of the 75 resulting soil-vegetation associations the soil organic carbon density was calculated as the median of the carbon density of soil profiles in the corresponding association (Bernoux et al., 2002). For France, an estimate of soil organic carbon to a depth of 30 cm was made using a combination of geo-referenced soil and land use databases (Arrouays et al., 2001). Lettens et al. (2004) divided Belgium into landscape units by the topological intersection of a land cover geo-data set and a soil association map. After excluding urban areas and military domains, 492 landscape units remained with an average polygon size of 30 ha.

## 6.1.2. Soil type & SOC

Soil texture strongly influences C dynamics. The high surface area of the fine silt and clay fractions enhances formation of organo-mineral complexes that protect C from microbial oxidation (Grigal & Berguson, 1998). Thus, clay minerals bind and protect organic matter, and residues typically decompose more rapidly in sandy than in clay soils (Sorensen, 1981). With the exception of some soils of basaltic origin (Spain, 1990), amounts of organic matter have been related to clay content over a wide range of soils (Bird, 2000). Especially high surface charged clays attract oppositely charged functional groups of various organic molecules that protect them from decomposition (Crasswell & Waring, 1972).
Batjes (1996) made an estimation of organic carbon contents of FAO-UNESCO soil units of the world. Table 6.1 presents his results for the 0-1m depth interval for the soils that are prevalent in our study area. In this study Phaeozems, Gleysols and Vertisols have the highest SOC content, while Arenosols contain the least C.

***Table 6.1 Mean (Batjes, 1996) and median (Sombroek et al., 1993) SOC stocks of the main soil units (by FAO-UNESCO) that are also found in the study area.***

| Soil unit | | SOC ($Mg.ha^{-1}$; 1m depth) | |
|---|---|---|---|
| General | Qualifier | Batjes (1997) | Sombroek et al. (1993) |
| Acrisols | | 94 | 71 |
| | Ferric | 67 | |
| | Humic | 203 | 178 |
| Ferralsols | | 107 | 145 |
| | Acric | 102 | |
| | Humic | 190 | |
| | Plinthic | 101 | |
| | Rhodic | 91 | |
| Gleysols | | 131 | 119 |
| | Calcaric | 50 | |
| | Eutric | 97 | |
| | Humic | 293 | |
| | Mollic | 168 | |
| Phaeozems | | 146 | 141 |
| | Haplic | 150 | |
| | Luvic | 156 | |
| Fluvisols | | 93 | 102 |
| | Eutric | 109 | |
| Nitisols | | 84 | 94 |
| | Dystric | 81 | |
| | Humic | 182 | |
| Arenosols | | 31 | 26 |
| | Albic | 34 | |
| | Ferralic | 37 | |
| Vertisols | | 111 | 94 |
| | Chromic | 95 | |
| | Pellic | 132 | |

## 6.1.3. Land use, land use change & SOC

Each soil has a C carrying capacity, i.e. an equilibrium C content depending on the nature of vegetation, precipitation and temperature (Gupta & Rao, 1994). The equilibrium C stock is the result of a balance between the rate of SOC inputs and rate of mineralization in the organic C pools (Fearnside & Barbosa, 1998). The SOC storage of natural undisturbed forest is at near steady state with annual inputs of detritus material from above- and below-ground sources equal to annual respiration. Average carbon stocks in tropical forest soils (230 Mg C $ha^{-1}$) comprise about 60 per cent of total C stocks in tropical forests (447 Mg C $ha^{-1}$) (Malhi et al., 1999) and 11% of the world's soil carbon pool (Brown & Lugo, 1982). Veldkamp et al. (2003) reported that although SOC concentrations are low in highly weathered tropical forest subsoils, the total stock is significant due to the soils' large worldwide volume. Further potential for maintaining current soil C stocks in tropical and subtropical regions can be found in conservation of wetlands and peat lands (Batjes, 2004). According to Batjes (2004), C stocks in East Africa range from 72 to 75 Mg C $ha^{-1}$ (1m depth).

The equilibrium between carbon inflows and outflows in soil is disturbed by land use change until a new equilibrium is eventually reached in the new ecosystem (Guo & Gifford, 2002). Conversion of natural

vegetation to various land uses results in very rapid declines in soil organic matter (SOM) (Mann, 1986; Davidson & Ackerman, 1993) and a release of C into the atmosphere (Houghton, 1995). Globally, the long-term flux of C from changes in land use (1850-2000) released 165 Pg C into the atmosphere, about 60% of it from the tropics and 8% from tropical Africa. Average annual flux during the 1990s was 2.2 Pg C $yr^{-1}$, dominated by releases of carbon from tropical deforestation (Houghton, 2003). Deforestation and cultivation of previous forest areas generally decreases soil C stocks by 25% globally and by 35% in the tropics (Brown & Lugo, 1982). The average release of soil C in the top meter soil per ha of deforestation measures 14.2 Mg C $ha^{-1}$ in the tropics, and 12.3 Mg C $ha^{-1}$ in Africa (Fearnside, 2000).

Soil C sequestration can be achieved by increasing the net flux of C from the atmosphere to the terrestrial biosphere as global net primary productivity (NPP), thus increasing C inputs in the soil, and storing a larger proportion of the carbon from NPP in the longer term C pools in the soil, or by slowing down decomposition (Smith, 2004). The global estimates for C sequestration potential in soils range between 1Pg C $yr^{-1}$ (IPCC, 1996) and 2 Pg C $yr^{-1}$ (Metting et al., 1999), that is, between one-third and two-thirds of the annual increase in atmospheric C levels (Smith, 2004).

The rate and direction of change in SOC after conversion depends on a number of factors including soil type, climate, topography, method of clearing and land use before and after (Vågen et al., 2005; Post & Kwon, 2000).

Not only input and mineralisation rates influence the final amount of SOC after land use change, but also soil erosion. Soil erosion is a four-stage process involving detachment, breakdown, transport/redistribution and deposition of sediments. The SOC pool is influenced during all four stages. Being a selective process, erosion preferentially removes the light organic fraction of a low density of < 1.8 $Mg.m^{-3}$. A combination of mineralization and C export by erosion causes a severe depletion of the SOC pool on eroded compared with uneroded or slightly eroded soils. In addition, the SOC redistributed over the landscape or deposited in depressional sites may be prone to mineralization because of breakdown of aggregates leading to exposure of hitherto encapsuled C to microbial processes among other reasons. Erosion-induced emission may be 0.8-1.2 $Pg.yr^{-1}$ on the earth. Thus, soil erosion has a strong impact on the global C cycle and this component must be considered while assessing the global C budget (Lal, 2003).

## 6.1.4. Factors influencing SOC after LUC

### *6.1.4.1. Soil type*

Changes in SOC stocks following land use change (LUC) may be different among soil types as a result of differences in soil texture, initial fertility level and underlying parent material.

There are discrepancies among studies that have compared change in soil C following land use change in soils of different texture. After aforestation, some authors (Giddens et al., 1997; Tate et al., 1997; Scott et al., 1999) have found that the change in soil C was least in clay soils while others (Lugo et al., 1986) have found that the rate of soil C accumulation was directly related to clay content, the relationship between C accumulation and soil texture being strongest at higher soil C contents. These discrepancies could be

related to the type or chemical composition of the clay minerals, or to the time period considered. Kaolinitic clays with low surface activity may not offer the same degree of physical protection to soil organic matter and microbial biomass that montmorillonitic clays with high surface activity provide (Franzluebbers, 1999). Reviewing 36 agricultural studies worldwide, Allen (1985) found that in tropical old parent material soils, organic C, total N, and CEC decreased 50% more than in other soil types.

Paul et al. (2002) found that temporal effects were particularly important in soils with high clay content where, in the short-term, large quantities of C, previously protected in organo-mineral complexes, may be released during site preparation while, in the longer term, clayey soils have the potential to accumulate large quantities of C.

Continuous cropping with sisal on Ferralsols in the coastal plain of Tanzania resulted in serious fertility decline and a significant lower SOC content in the topsoils, although there were little differences in the subsoils. Under Acrisols no significant difference was found, and Arenosols had very low levels of OC under both bush vegetation and permanent cropping. Soil fertility hardly changed in Cambisols, Leptosols, Luvisols and Phaeozems. The differences in degradation rates were explained by the lower initial fertility and low nutrient reserve of Ferralsols, while the Cambisols had higher initial fertility levels and nutrients removed are replenished by weathering of the underlying parent material (Hartemink & Bridges, 1995; Hartemink, 1997). In Southern Tanzania, organic matter contents in a Luvic Arenosol soil ranged between 1.28% in soils with a history of organic residue removal and 1.80% in a soil to which goat manure had been added. In a Rhodic Ferralsol soil however the OM content ranged between 1.09% and 3.38% respectively (Majule, 1999).

#### *6.1.4.2. Land use*

The major factor determining the rate of accumulation or loss is the quantity and quality of organic matter inputs (Post & Kwon, 2000). Woody plants produce big amounts of recalcitrant material. After forest removal high losses in SOC can be attributed to reduced inputs of organic matter. The C initially held in trees and other vegetation is released through burning or through decomposition of above- and belowground plant material left in the soil at the time of clearing. Even if the productivity of the new agricultural land is as high as it was in the forest, less of the crop production accumulates as litter; most of it is harvested and subsequently consumed or respired. The rapid declines in soil organic matter are further due to an increase in SOC oxidation due to higher soil surface temperatures in arable soils as compared to soils under forests (Hartemink et al., 2008) and a lower fraction of non-soluble material in the more readily decomposed crop residues (Post & Kwon, 2000).
Another factor, which influences the SOC change after land use change, is the placement of OC inputs. Woody plants may be less effective than perennial grasses in some environments at storing C in soil (Brejda, 1997) since they deposit a larger fraction of total inputs than both grasses and pastures on the surface where decomposition conditions are generally more favourable (Post & Kwon, 2000).
Erosion and soil chemical changes can be significant when the canopy is not closed and the soil is not covered after land conversion (Hartemink et al., 2008).

Guo & Gifford (2002) found an average significant increase in C stocks after the conversion from forest to pasture (+8%), crop to plantation (+18%), crop to secondary forest (+53%) and crop to pasture

(+19%). Soil C declined after the conversion from pasture to plantation (-10%) and particularly from forest and pasture to crop (-42% and -59% respectively). When native forest is cleared for plantation forestry, soil C stocks are unaffected by broadleaf plantations and by pine plantation in low rainfall areas but decline where rainfall exceeds 1500 mm.yr$^{-1}$ (-56%). In humid and sub-humid sub-Saharan Africa SOC stocks decline by 24.30 Mg.ha$^{-1}$ when natural forest is converted to cultivated land and 4 Mg.ha$^{-1}$ after conversion to fallow (Vågen et al., 2005). In Miombo woodlands of Malawi, SOC stocks reduced from 83 Mg.ha$^{-1}$ to 49 Mg.ha$^{-1}$ when converted to agricultural land and to 52 Mg.ha$^{-1}$ under fallow (Walker & Desanker, 2004). However, a distinction needs to be made between pastoral agriculture, arable agriculture and mixed farming involving crop/pasture sequences (Guo & Gifford, 2002). It also matters whether forest is converted to cropland with annual crops (e.g. maize, cassava or soybeans), perennial crops (e.g. oil palm, cocoa or rubber) or forest plantations. The conversion to perennial crops usually results in lower levels in the rates soil fertility decline because – to some extent – these systems mimic the forest cover (Hartemink et al., 2008).

Quantifying changes in SOC upon aforestation is also complex. Globally, areas previously under grassland show no change or a slight decrease in SOC following aforestation (Paul et al., 2002). After aforestation of previous agricultural land, average data indicate that soil C is initially decreasing before increasing so that, after about 30 years, C within the surface 30 cm of soil is greater than that in the previous agricultural soil (Aweto, 1981; Zak et al., 1990, Richter et al., 1999; Vesterdal et al., 2002). However Vesterdal et al. (2002) hypothise that aforestation on more nutrient-poor sandy parent materials could result in faster changes in soil C due to slower decomposition rates. Vågen et al. (2005) confirm these relationships for soils of Sub-Saharan Africa: conversion of cultivated land to fallow increased SOC stocks by 1.38 Mg ha$^{-1}$, to forest by 1.97 Mg ha$^{-1}$ and to agro-forestry (improved fallow) with 6 Mg ha$^{-1}$ depending on the type of agroforestry system used and the soil types. This process could not fully recover the amount of carbon lost from soil during the process in the other direction except for the establishing of secondary forest.

In fallow systems, the initial size of the SOC stock at the beginning of the fallow period largely determines the rate of regeneration and long-term trends in SOC dynamics (Nye & Greenland, 1960; Szott et al., 1999). Swaine and Hall (1983) reported substantially higher SOC stocks after four years of fallow (~83.3 Mg C ha$^{-1}$) than in natural forest (~63.5 Mg C ha$^{-1}$) in humid forests in Ghana. Studies conducted in the humid natural forest zone of Madagascar showed a rapid increase in SOC in the first two years of fallow (Brand & Pfund, 1998). Kotto-Same et al. (1997) reported re-accumulation rates in recovering fallows to be approximately 9.4 Mg C ha$^{-1}$ in a six-year fallow period. Several studies have shown decreasing SOC contents during the first five to eight years of fallow following clearing of natural forest with SOC increasing and stabilizing at levels similar to natural forest systems after 12 to 15 years. Juo et al. (1995) reported a decrease of 12 Mg C ha$^{-1}$ (0–15 cm depth) in SOC after seven years of fallow and a recovery to levels similar to those at clearing after 12 to 13 years.

#### *6.1.4.3. Climate*

Jenny (1980) indicated that of several variables influencing the capacity of soils to store soil organic matter, mean annual precipitation exerts the greatest influence. Higher rainfall, despite the advantage of moister soil for decomposition, is thought to be associated with a larger soil organic C pool and greater leaching of C to the deep profiles (Jenny, 1980; Post et al., 1982). Therefore, if soil structure is disturbed

after land use change, for example through site preparation, C leaching may play some role in the reduction of soil C stocks in the areas with high annual precipitation (Guo & Gifford, 2002).

In soils with high availability of moisture, rates of decomposition are directly related to the average annual temperature (Brown & Lugo, 1990; Nilsson et al., 1995). Low amounts in tropical soils are attributed to rapid decomposition, which compensates for large litter production (Post et al., 1982; Huntington, 1995). In tropical forests, Brown & Lugo (1982) found a significant negative exponential relationship between soil carbon and T/P (temperature/precipitation). Both the variability and upper limit in the carbon content of soil decrease with increasing T/P (i.e. towards the drier life zones) (Figure 6.1).

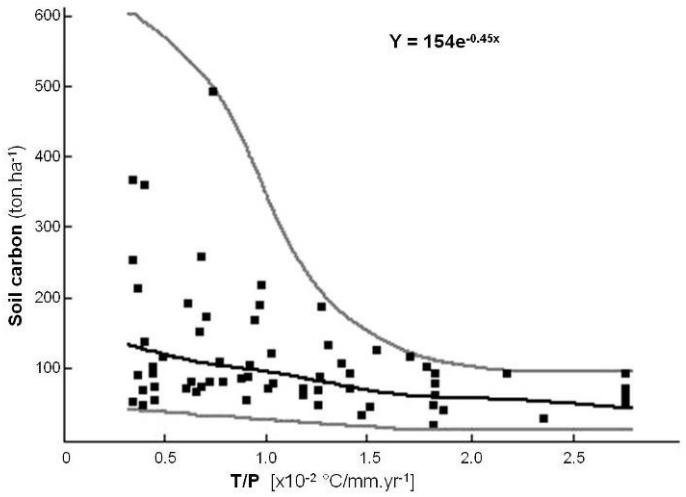



***Figure 6.1 Relationship between SOC content and temperature (T°C) to precipitation (P mm yr$^{-1}$) ratio. The statistical line is inside the envelope used to accentuate the range of values (Brown & Lugo, 1982).***

Guo & Gifford (2002) found that clearing of forest for pasture in areas with 2000-3000 mm precipitation sequestered significantly more soil C stocks than in other areas with either lower or higher rainfall. They suggested that conversion of forest to pasture in areas with higher annual rainfall led to initial topsoil erosion and associated loss of C, which was only gradually recovered under pasture.

### *6.1.4.4. Method of clearing*

The method of converting one land cover to another will influence the rate of SOC change. In case of burning, fire intensity and ambient weather conditions affect the amount of SOC lost (Bruijnzeel, 1998). Hotter fires can increase soil C in sub-surface horizons because of the transport of hydrophobic organic matter from surface soil and subsequent stabilization with cations (Giovannini et al., 1987). Low-temperature fires (e.g. prescribed burning) generally result in either no change or an increase in soil C, due to incorporation of charcoal and partially burned organic matter into mineral soil. However, burning decreases C in the forest floor (Paul et al., 2002).

Tillage activities cause mixing and stirring of soil, break up aggregates and expose organo-mineral surfaces otherwise inaccessible to decomposers and thus will result in a decline in soil organic matter (Post & Kwon, 2000).

### *6.1.4.5. Management*

Best management practices for croplands will often encompass a combination of the following options: (a) conservation tillage in combination with planting of cover crops, green manure and hedgerows; (b) organic residue and fallow management; (c) mulch farming, especially in dry areas; (d) water management, including in situ water conservation in the root-zone, irrigation, and drainage to avoid potential risk of

salinization and water-logging; (e) soil fertility management, including use of mineral fertilizers and organic wastes, liming and acidity management; (f) introduction of agro-ecologically and physiologically adapted crop/plant species, including agro-forestry; (g) adapting crop rotations and cropping/farming systems, with avoidance of bare fallow; and (h) stabilization of slopes and terraces to reduce erosion risk (Batjes, 2004). In Nigeria, Van Noordwijk et al. (1997) suggested that it is possible to maintain SOC levels fairly close to that under forest through management systems that do not increase pH and minimize tillage.
At sites where nutrients are limiting production, application of fertilizer increases plant productivity and hence the amount of C input to soil (Nilsson et al., 1995), yet may also lead to better litter quality and therefore faster rates of decomposition (Conteh et al., 1997). Although some long-term agricultural field trials have demonstrated that fertilizer application significantly decreases, or has no effect on soil carbon (Collins et al., 1992; Hassink, 1994), most researchers have observed that soil carbon increases due to fertilizer application (Johnson, 1992).

### 6.1.5. At which depth?

Changes in soil carbon after conversion vary significantly with soil sampling depth. Globally conversion of forest to pasture or crops has no influence on soil C stocks beyond 60 cm depth, but it significantly reduced carbon above the 60 cm depth (Guo & Gifford, 2002). In tropical forest soils the highest concentrations of SOC are observed in the top 0–20 cm depth and SOC in topsoil is more labile than that in the subsoil and more prone to change upon deforestation and other perturbations (Veldkamp et al., 2003). Data from long-term studies in Senegal show changes in SOC below 10–20 cm depth to be minor after conversion (Siband, 1974).

The litter layer may hold large amounts of C, especially in forests (Paul et al., 2002). Numerous studies have demonstrated a decrease in C in the mineral soil, but a net increase or insignificant change in soil C after aforestation when the litter layer is included in calculations (Richter et al., 1995; Gifford, 2000; Paul et al., 2002). For example, under Loblolly Pine (Pinus *taeda* L.) established on previously cultivated soil, Richter et al. (1999) found that about 96% of the accumulated C was in the forest floor.

### 6.1.6. Which time span?

The period for soils in a temperate location to reach a new equilibrium after a land use change is around 100 years (Jenkinson, 1988; Smith et al., 1996) but tropical soils may reach equilibrium more quickly. As a compromise, current IPCC Good Practice Guidelines for Greenhouse Gas Inventories use a figure of 20 years for soil carbon to approach a new equilibrium (IPCC, 1997; Paustian et al., 1997).

## 6.2 Problem statement and aim

It has already been discussed in Chapter 4 that land use change and deforestation have been major causes of $CO_2$ emissions in Tanzania and in the study area.
Factors which further inhibit the build up of organic matter in large areas of southeastern Tanzania are: i) severe soil physical conditions, ii) high temperatures that increase the rate of organic matter decomposition and hence carbon loss and iii) termite attacks of residues prior to the incorporation into the soil (Majule, 1999). Bennett et al. (1979) mentioned soil physical constraints in some regions of the

study area (see Chapter 3). The soils on the plateaus and uplands have small amounts of low-activity clays and thus very low nutrient-holding capacities, very low base saturations and no weatherable minerals. Except for areas where nutrients can be concentrated at the surface by vegetation, this is an area of very low soil fertility and potential. The higher plateau areas also suffer from moisture stress. In the southern plains coarse sandy infertile soils and a dry climate constrain development (Bennett et al., 1979). In general, the 6-month rainy season occurs during the warmest months (Bennett et al., 1979) which constraints the accumulation of organic matter. The effect of termite attacks on SOC will be further discussed in Chapter 8.

Despite these negative findings, it has been shown in Chapter 2 that many areas in southeastern Tanzania have the potential for holding considerable amounts of SOC. Yet it is still unclear how these different soil units may explain different changes in SOC stocks after land conversion. With remnants of native forest, areas of bush and woodland, fallow systems, cashew plantations and many different crops, the difficult task of unravelling the effect of conversion from one land use to another on SOC stocks has not yet been accomplished.

Therefore the main questions of this chapter are:
What is the impact of different soil types on the SOC stock? What is the impact of different land uses and land use change on the SOC stock? Does the effect of land use depend on the soil type and which soil is most sensitive to land use change? What is the effect of time after establishment of a land use? What is the total SOC stock in the study area, taking into account the spatial distribution of soil-landuse units (LSU)? How do these total SOC stocks evolve after land use changes have taken place?

# 6.3 Materials and methods

The datasets of ITCRP (1981) and Ngatunga (2001) contain information on soil type, land use and total SOC stocks (calculated in the previous chapter). They can be used for this study, although no information is available on the state of the vegetation, the age and management of the fields or the land use history. The profiles described by Bennett et al. (1979) give no information on land use and can therefore not be used.

The data from these datasets were collected with a specific research scope in mind (see paragraph 2.3.1); therefore it may not be the optimal dataset for SOC mapping. Gaps in certain soil or land use groups will have to be filled. For example, Vertisols occur only locally, but their carbon storage capacity could be important. More information is also needed on the land use history, management and condition of fields. Therefore we conducted a new soil survey in 2005. In this survey 88 villages in the region were selected. The villages were chosen in all land units, except those north of Mbwemkuru River, due to practical reasons. Within the land unit, villages were chosen if possible on different soil types. The chairman and village elders gave information on the general history and current condition of village and fields and the most important land uses in the area. These different land uses were sampled in adjacent fields with identical soil and landscape properties and land use histories.
GPS coordinates, current land use and land use history, site management and environmental conditions were listed for each field. Based on an augering to 1.20m depth the soil was described using the

Guidelines for Soil Description (FAO, 2006). As discussed above, the main influence of land use change will appear in the upper soil layers, therefore samples were taken at the soil surface (0-5 cm) and in the second horizon (40-45 cm). In each field, 5 samples were taken with a ring sampler (volume = 100cm³), mixed, dried in the oven for 48 hours at 105°C, weighed, sieved through a 2 mm sieve and mixed again. SOM, SOC and bulk density and SOC densities to 1m depth were calculated as discussed in the previous chapter.
The combination of the old and new datasets generated 563 profiles with attributed SOC stock, soil type and land use.

The study area was divided into landscape units by intersecting the soil map (Figure 3.4) and the recent land use maps (Figure 4.3 b & c). This generated 424 landscape units (LSU) for the 1997 landuse map (Africover) and 225 units for the 2005 landuse map (Globcover). Not enough profiles are available to adequately represent every LSU, therefore soils were consolidated into 8 main groups. Solonchaks, Plinthosols and Fluvisols were represented by too few samples per land unit and no mean SOC stock was calculated for them. Mean SOC stocks were calculated for the 8 main soil groups by attributing the soil profiles to the soil groups with geomatching. This means that the mean SOC stock of the soil group is based on all profiles whose geographical position is located within the polygon of the soil group (Lettens et al., 2004; Van Orshoven et al., 1993). Since the soil map itself is based on these profiles, this will give a good match. The advantage is that the influence of two land uses established on the same soil type (e.g. a Ferralsol) on SOC can be compared. If one landuse increases the SOC in the A-horizon, it will be classified as a Phaeozem next to the other land use on a Ferralsol, and the effect of land use cannot be separated any more from the effect of soil type.

No geomatching can be used for the land use types since the soil samples were taken in different years than those of the satellite images on which the land use maps were based. Therefore classmatching (Lettens et al., 2004; Van Orshoven et al., 1993) is used for the land use types: only the profiles with the same land use as the LSU were attributed to that LSU. First ten land uses were distinguished: (closed) forest, woodland, bushland, tree crops (mainly cashew and a few coconuts), intercrop (cashew plantations under which several crops are grown, usually limited in space and time), fields with mainly cassava, crops (fields without cassava), rice fields, homestead gardens (intensively managed vegetable and fruit gardens close to the village, often fertilized or irrigated, including tomato, eggplant, banana, yam, amaranth, okra, cabbage…) and grasslands (Figure 6.2). These 10 land use groups were used in statistical analysis (see further). However, these 10 distinctions could not be made on the land use maps of Figure 4.3. For the scope of mapping, the groups were reduced to 6 simplified land use classes (forest, woodland, bushland, tree crops (including intercrops), crops (all types) and grassland). Mangrove forests and urban areas were not represented by enough samples to calculate SOC stocks.

SPSS software was used to conduct statistical analyses. Mean values and standard deviations were calculated for all land uses and soil types separately. General linear model (GLM) analysis showed that there was no interaction effect between soil type and land use, meaning that the effect of land use on SOC did not differ between soil types. Therefore differences between soil types and land uses were tested separately using ANOVA analysis (with $\alpha$=0.05). Although the interaction effect was not significant, the

exact values of SOC within all soil-land use combinations are of great interest and their mean values and standard deviations were calculated.

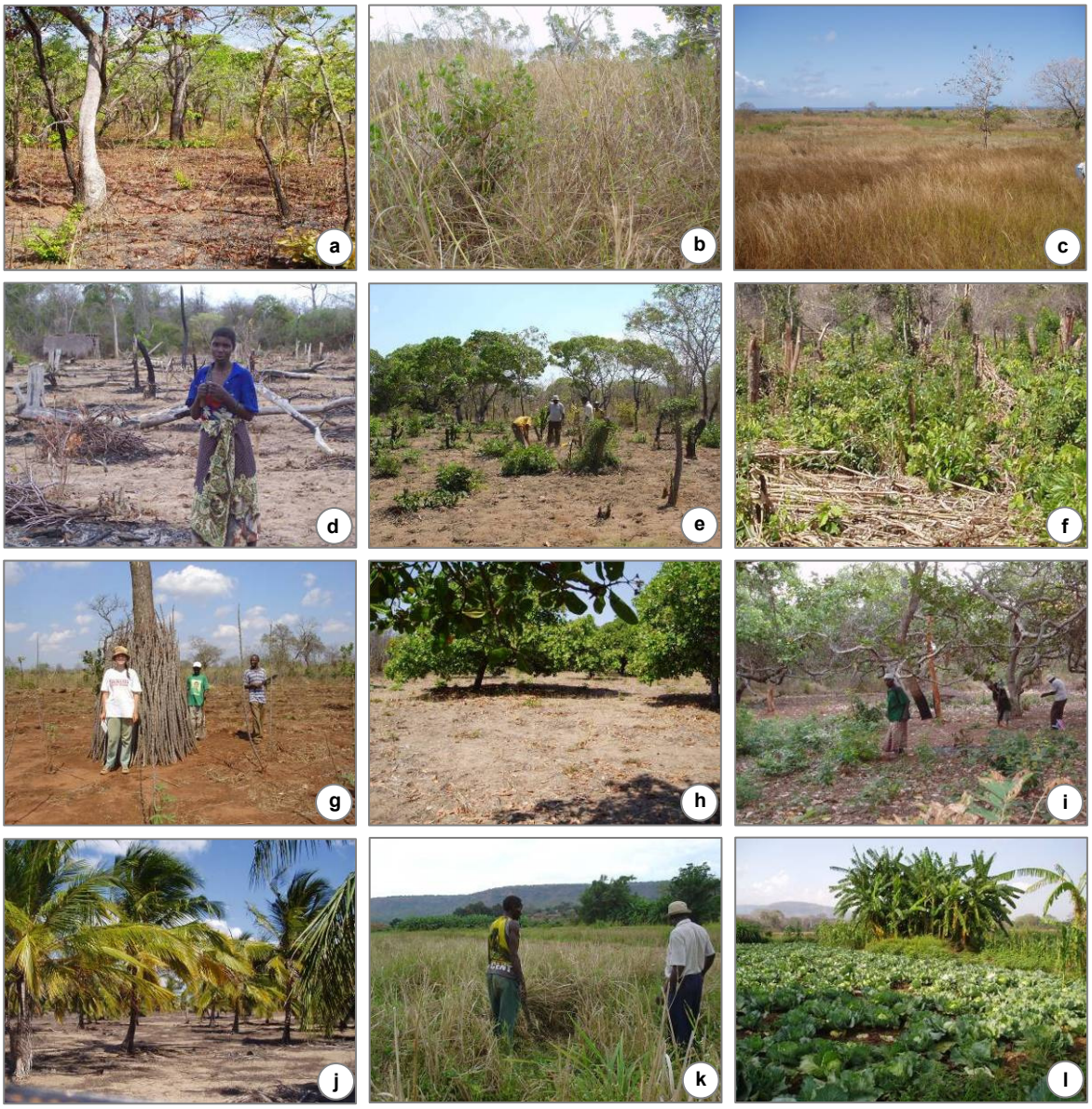



***Figure 6.2 Typical images of the main land uses in the study area: (a) miombo woodland, (b) young bush land, (c) grassland, (d) field just after clearing, (e) cropped field 1 year after clearing, (f) cropped field several years after clearing, (g) cassava field with pile of stems for vegetative propagation, (h) cashew plantation, (i) intercropped cashew plantation, (j) coconut plantation, (k) rice field, (l) homestead garden.***

The effect of age could only be tested on the new (2005) data, since they include information of the age of a field or bush fallow. Since 20 years is taken as a reference for a soil to approach a new equilibrium after land use change (IPCC, 1997; Paustian et al., 1997), the SOC stocks for bushlands, tree crops and agricultural fields are calculated for newly established (<20 years old) and old fields (>20 years old).

Two LSU maps were made in ArcView, by intersecting the soil map and the two landuse maps (from 1997 and 2005). Mean values of soil-land use combinations (based on the 6 simplified land use classes) were calculated and attributed to the LSU. When no SOC stocks were calculated for a LSU (e.g. for Plinthosol), the mean SOC of the land use was attributed to that LSU. Consequently, when no SOC was calculated for a land use (e.g. mangrove forest) the mean SOC stock of the soil type of that LSU was used. If a land use within a certain soil type was underrepresented by samples, e.g. Forests on Phaeozems, the SOC stock for that LSU was estimated by multiplying the ratio ($SOC_{forest}/SOC_{average}$) of all soils with the average SOC stock of Phaeozems. All SOC values were attributed to their LSUs on the intersected maps, which generated two SOC maps of the study area. The area of each LSU was calculated and multiplied with the SOC stock per LSU (in $Mg.ha^{-1}$, 1 m depth) and resulted in a total SOC stock for the region (in Mg C).

# 6.4 Results

## 6.4.1. SOC stocks in LSU

***Table 6.2 Statistics of SOC stocks ($Mg.ha^{-1}$; 1m depth) for different soil units of the study area. Like letters in the last column signify no significant differences between classes (α=0.05).***

| Soil units | N | Mean | Standard deviation | Significant difference |
|---|---|---|---|---|
| **Vertisols** | 31 | 140 | 92 | a |
| **Gleysols** | 30 | 87 | 70 | bde |
| **Phaeozems & Umbrisols** | 79 | 93 | 56 | b |
| **Ferralic/Arenic Phaeozems** | 104 | 55 | 51 | cd |
| **Alisols, Acrisols, Lixisols** | 131 | 68 | 50 | de |
| **Nitisols** | 43 | 107 | 57 | ab |
| **Ferralsols** | 77 | 57 | 46 | ce |
| **Arenosols** | 69 | 44 | 42 | cd |
| **Average** | 563 | 73 | 59 | |

Table 6.2 shows the effect of different soils on SOC stocks. Vertisols have the highest SOC stocks (140 $Mg.ha^{-1}$), which is twice as much as the average and significantly different from all other soils except Nitisols, which have the second highest SOC stock (107 $Mg.ha^{-1}$). The other clayey soils, Gleysols, have a mean C stock that is above average but much lower than the two previous ones (87 $Mg.ha^{-1}$). Phaeozems and Umbrisols are soils with typically a high C concentration in the topsoil. However Haplic or Luvic Phaeozems and Umbrisols have significantly higher SOC stocks (93 $Mg.ha^{-1}$) than Ferralic or Arenic (55 $Mg.ha^{-1}$). Acrisols, Lixisols and Alisols with an illuvial texture-B-horizon ($B_t$-soils), have mean SOC stocks (68 $Mg.ha^{-1}$) close to the average. SOC stocks in Ferralsols and Arenosols (respectively 57 and 44 $Mg.ha^{-1}$) are significantly lower than in Vertisols, Nitisols and Phaeozems.

***Table 6.3 Statistics of SOC stocks (Mg.ha$^{-1}$; 1m depth) for different land uses of the study area. Like letters in the last column signify no significant differences between classes (α=0.05).***

| Land use | N | Mean | Standard deviation | Significant difference |
|---|---|---|---|---|
| **Forest** | 4 | 66 | 20 | abc |
| **Woodland** | 88 | 68 | 47 | ae |
| **Bushland** | 73 | 105 | 67 | c |
| **Tree crop** | 137 | 50 | 43 | ab |
| **Intercrop** | 110 | 69 | 59 | bde |
| **Cassava** | 56 | 39 | 35 | a |
| **Crop** | 45 | 98 | 58 | ce |
| **Rice** | 18 | 114 | 68 | cd |
| **Garden** | 18 | 128 | 94 | c |
| **Grassland** | 14 | 118 | 60 | ce |
| **Average** | 563 | 73 | 59 | |

The effect of land use is demonstrated in Table 6.3. The highest SOC stocks are found in bushland (105 Mg.ha$^{-1}$), rice fields (114 Mg.ha$^{-1}$), homestead gardens (128 Mg.ha$^{-1}$), grasslands (118 Mg.ha$^{-1}$) and cropland (98 Mg.ha$^{-1}$) (all not significantly different from each other). Woodlands have significantly lower SOC stocks (68 Mg.ha$^{-1}$) than bushlands, and even closed forests have lower SOC contents, although this is only based on 4 samples. The lowest SOC is found under cassava fields (39 Mg.ha$^{-1}$), which is significantly less than other crops. Tree crops, mainly cashew, which are the most important land use in the study area, contain less than half (50 Mg.ha$^{-1}$) of the SOC of bushlands. This increases by 19 Mg.ha$^{-1}$ when they are interplanted with crops.

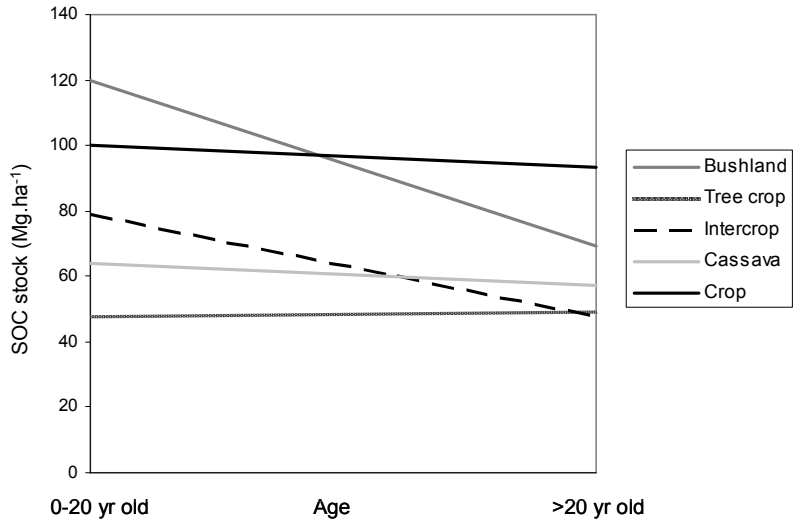



***Figure 6.3 SOC stocks against age after establishment (0-20 years and >20 years) for the new dataset (n=336).***

The effect of field age after establishment of the field can be obtained from Figure 6.3. It is clear that young bushlands have much higher SOC stocks (120 Mg.ha$^{-1}$) than old bushlands (70 Mg.ha$^{-1}$), which

come close to the SOC stock of woodlands. Tree crops intercropped with other crops have initially higher SOC stocks (79 Mg.ha$^{-1}$) than tree crops without intercrops (48 Mg.ha$^{-1}$). No distinction was made between cassava and other crops. After more than 20 years their SOC stock equals that of tree crops without intercrops. SOC stocks of other crops remain fairly constant with age.

***Table 6.4 SOC stocks (Mg.ha$^{-1}$, 1m depth) (mean, standard deviation and number of samples) for soil type-land use combinations in the study area. Numbers displayed in grey are based on only 1 or 2 samples and have to be considered with caution.***

| **Soil type** | Vertisols | | | Gleysols | | | Phaeozems Umbrisols | | | Ferralic/ Arenic Phaeozems | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Land use** | Mean | SD. | N | Mean | SD. | N | Mean | SD | N | Mean | SD | N |
| **Forest** | | | | | | | 67 | | 1 | | | |
| **Woodland** | | | | | | | 79 | 54 | 15 | 53 | 32 | 23 |
| **Bushland** | 164 | 114 | 9 | 106 | 73 | 8 | 124 | 51 | 14 | 113 | 49 | 5 |
| **Tree crop** | 105 | 106 | 2 | 33 | 37 | 6 | 54 | 31 | 14 | 42 | 38 | 22 |
| **Intercrop** | 140 | 79 | 3 | 46 | 34 | 2 | 82 | 45 | 8 | 58 | 70 | 24 |
| **Cassava** | | | | 19 | 2 | 2 | 58 | 33 | 5 | 45 | 45 | 18 |
| **Crop** | 92 | 51 | 8 | 166 | 32 | 2 | 101 | 42 | 10 | 52 | 27 | 6 |
| **Rice** | 144 | 67 | 4 | 139 | 83 | 5 | 76 | 49 | 4 | | | |
| **Gardens** | 220 | 156 | 3 | 79 | | 1 | 185 | 54 | 4 | 89 | 85 | 4 |
| **Grassland** | 131 | 8 | 2 | 86 | 50 | 4 | 158 | 61 | 4 | 64 | 37 | 2 |

| **Soil type** | Alisols Lixisols Acrisols | | | Nitisols | | | Ferralsols | | | Arenosols | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Land use** | Mean | S.D. | N | Mean | S.D. | N | Mean | S.D. | N | Mean | S.D. | N |
| **Forest** | 79 | | 1 | | | | 58 | 30 | 2 | | | |
| **Woodland** | 73 | 46 | 25 | 120 | 58 | 7 | 48 | 29 | 12 | 49 | 54 | 6 |
| **Bushland** | 86 | 48 | 20 | 68 | | 1 | 90 | 52 | 10 | 61 | 37 | 6 |
| **Tree crop** | 59 | 53 | 34 | 77 | 55 | 8 | 49 | 41 | 20 | 38 | 29 | 31 |
| **Intercrop** | 66 | 54 | 27 | 104 | 58 | 15 | 57 | 51 | 20 | 47 | 41 | 11 |
| **Cassava** | 41 | 27 | 14 | 124 | | 1 | 31 | 22 | 8 | 14 | 5 | 8 |
| **Crop** | 81 | 53 | 4 | 132 | 67 | 7 | 72 | 70 | 4 | 118 | 86 | 4 |
| **Rice** | | | | 117 | 50 | 4 | | | | 7 | | 1 |
| **Gardens** | 81 | 41 | 5 | | | | | | | 55 | | 1 |
| **Grassland** | 143 | | 1 | | | | 149 | | 1 | | | |

SOC stocks for all soil type-land use combinations are shown in Table 6.4. Values in grey are based on 2 samples or less and will not be taken further into account. In all soil types, bushland, rice, gardens, crops and grasslands have the highest SOC stocks. Tree crops and cassava have on most soils the lowest SOC stock. Forests and woodlands have less SOC than bushland.

In all soils, the SOC stock of woodland is very close to the average SOC stock. The average SOC stock is taken as a reference situation and is compared to the SOC stocks of other land uses within that soil type to give an idea of the susceptibility of that soil type to land use changes. The increase in SOC from the mean value to bushland is below 25 Mg.ha$^{-1}$ for most soils. However it is above 30 Mg.ha$^{-1}$ for Phaeozems & Umbrisols, Ferralic/Arenic Phaeozems and Ferralsols. No data are available for Nitisols. SOC stocks decline compared to the average value when planting cashew by more than 30 Mg.ha$^{-1}$ in Gleysols, Phaeozems & Umbrisols and Nitisols. It declines by less than 15 Mg.ha$^{-1}$ in all other soils. Not enough data are available for Vertisols. Planting cassava reduces the average SOC stock with about 30 Mg.ha$^{-1}$ in all soils except for Ferralic/Arenic Phaeozems, where it only reduces by 10 Mg.ha$^{-1}$.

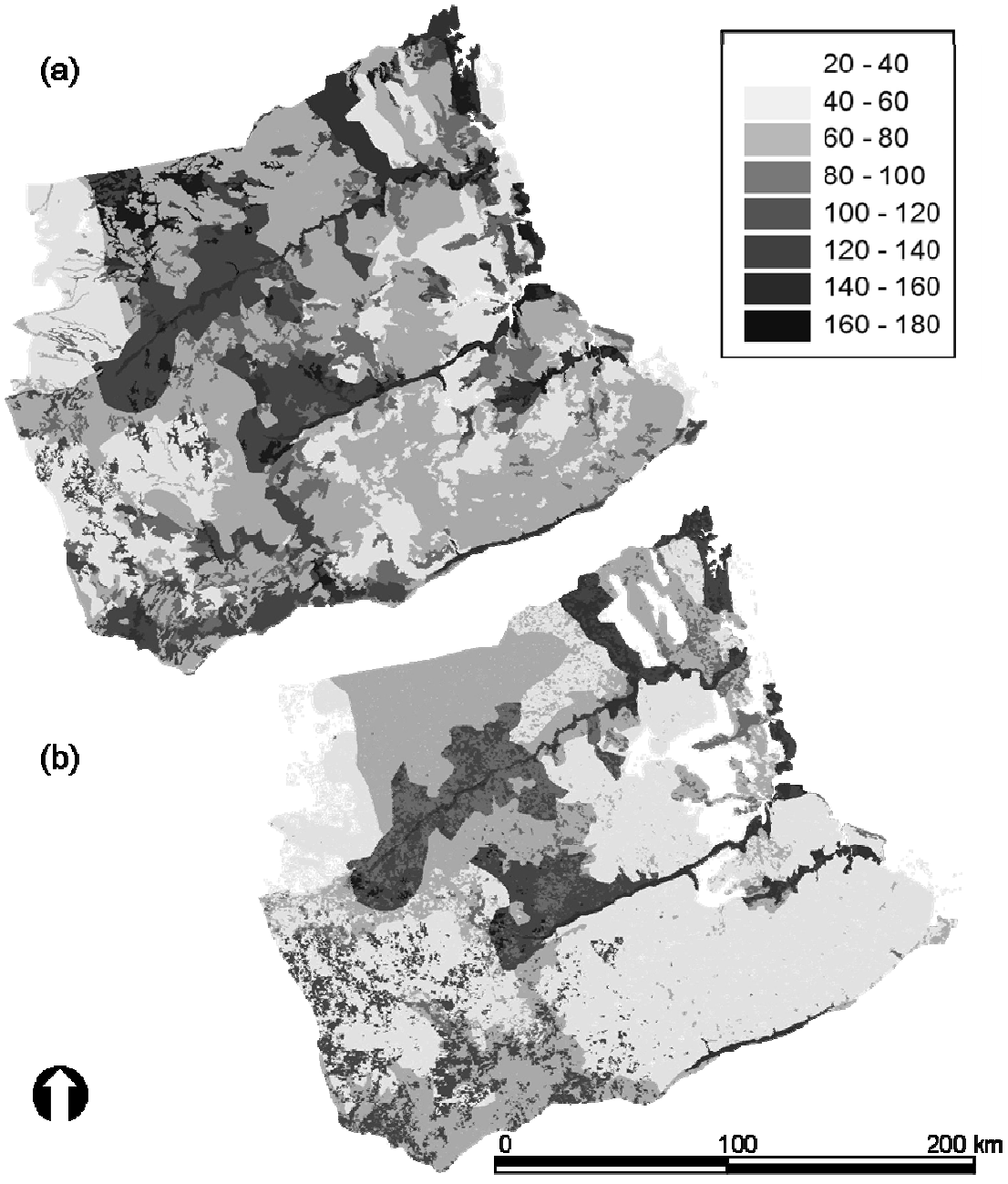



***Figure 6.4 Mean SOC stocks (Mg.ha$^{-1}$, 1m depth) for landscape units based on the soil map and the following landuse maps from (a) 1997 (Africover) and (b) 2005 (Globcover).***

Not enough data are available for Vertisols and Gleysols. Interplanting of tree crops improves the SOC stock compared to plain tree crops by respectively 27 and 28 $Mg.ha^{-1}$ in Nitisols and Phaeozems/Umbrisols. In the other soils this is less than 10%. Not enough data are available for Vertisols and Gleysols.

In the introduction of the previous chapter it was discussed that in some cases mass equivalents are a more useful unit for measuring SOC than carbon densities to a certain soil depth (in this case 1m). By using fixed depths, SOC may be overestimated in high bulk density soils, especially as the result of treatments. Therefore an ANOVA test ($\alpha$=0.05) was run on the new soil data (354 profiles, sampled at two depths) to estimate the relationship between bulk density and land use. In most soil types bulk densities were higher under tree crops, intercrops and cassava fields compared to other land uses and this effect was significant in the A-horizon. This can be explained by a high disturbance and trampling of the field by farmers in combination with very low organic carbon levels. This results in an overestimation of the SOC stocks in this type of land use. This effect will only reinforce our results, where tree crops, intercrops and cassava fields have among the lowest SOC stocks.

## 6.4.2. SOC maps & total SOC stocks

The values attributed to the landscape units are represented for 1997 and 2005 in Figure 6.4. Concentrations of high SOC stocks are clearly observed in Nitisol and Vertisol areas and under grasslands. Major changes between 1997 and 2005 can be seen on the plateau areas, due to the replacement of bushland by cashew.

***Table 6.5 Total SOC stocks for every soil group of the study area based on the Africover and Globcover land use maps; and the change in SOC between them.***

| Soil type | Area (kha) | SOC stock (Tg = $10^{12}$g) | | SOC loss 1997 – 2005 (Tg) |
|---|---|---|---|---|
| | | 1997 (Africover) | 2005 (Globcover) | |
| **Vertisols** | 22.4 | 3.09 | 2.75 | 0.34 |
| **Gleysols** | 12.7 | 1.09 | 0.83 | 0.26 |
| **Phaeozems & Umbrisols** | 97.5 | 9.40 | 7.83 | 1.57 |
| **Ferralic/Arenic Phaeozems** | 64.7 | 4.42 | 4.18 | 0.24 |
| **Alisols, Acrisols, Lixisols** | 86.4 | 6.44 | 5.37 | 1.07 |
| **Nitisols** | 38.7 | 4.66 | 4.19 | 0.46 |
| **Ferralsols** | 49.1 | 3.04 | 2.42 | 0.62 |
| **Arenosols** | 40.5 | 2.07 | 1.72 | 0.35 |
| **Other soils** | 3.3 | 0.29 | 0.22 | 0.07 |
| **Total** | 415.2 | 34.50 | 29.51 | 4.98 |

In Table 6.5 the total SOC stocks for the study area is estimated at 34.50 Tg. Large amounts of SOC are found in Phaeozems & Umbrisols, Ferralic/Arenic Phaeozems and $B_t$-soils, due to the large extend of these soils. Vertisols and Nitisols also contribute largely to the total SOC stock because of the high C concentrations in these soils. Land use changes between 1997 and 2005 decreased SOC stocks by almost 5 Tg, spread over all soil types. The largest effect was observed on the most common soils: Phaeozems and Umbrisols. The largest change, relative to the area of the soil type, was observed in Gleysols, Phaeozems and Umbrisols. These soils were previously described as sensitive to land use changes.

## 6.5 Discussion

Average SOC stocks are not uncommon for the region: Batjes (2004) and De Pauw et al. (1996) found SOC stocks ranging between 72 and 82 $Mg.ha^{-1}$ in similar African environments. Vertisols, Nitisols and Gleysols and Phaeozems have the highest stocks, and Arenosols the lowest, which is comparable to the data of Table 6.1 from Batjes (1996). High amounts of SOC in clayey soils as the result a high surface area and the formation of organo-mineral complexes have been described in literature. However much depends on the type of clay. High surface charged clays such as montmorillonite or smectite are found in Vertisols, which indeed have the highest SOC stocks. Nitisols contain more kaolinite and illite, which have a lower surface charge (Van Breemen & Feijtel, 1990). These minerals typically form micro-aggregates of silt ('pseudo-silt') or sand ('pseudo-sand') (Driessen & Dudal, 1991), but the total SOC stock is lower than in Vertisols. Gleysols planted with rice have similar SOC stocks compared to Vertisols.

However, the SOC stock under bushland is lower. This is probably the result of the impeded growth of vegetation on the wet and often Calcaric or Sodic Gleysols.

Phaeozems and Umbrisols are soils with a typically higher C concentration in the topsoil. Haplic and Luvic Phaeozems in the study area were mostly found on loamy material. C concentrations remain high in the subsoil, resulting in SOC stocks which are not significantly different from Gleysols or Nitisols. However, when these fertile topsoils are located on sandy subsoils, as in Ferralic and Arenic Phaeozems, they hardly contribute to the total SOC stocks, which are not significantly different from Ferralsols or Arenosols.
Alisols, Acrisols and Lixisols are very common soils in the study area. They often occur on slopes on sandy loam or loamy sand. All three soils have a clay increase in the $B_t$-horizon, which can retain a certain amount of organic carbon. Ferralsols, which are often formed in the same parent material but without the $B_t$ horizon, have lower SOC stocks, although not significant. The sandy Arensols have the lowest SOC stock.

Significant differences were found between SOC stocks of different land uses.
Closed forests are supposed to have been the original vegetation type of a large part of the study area. Most of these forests have been removed or strongly degraded. The low SOC stocks in these forests, which can be compared to those in woodlands, can be attributed to the degraded state of this vegetation type and to the fact that these forests only remain on the poorest soils. Therefore, it is impossible to make any assumptions on the SOC stocks under the original vegetation cover.

Miombo woodlands are the natural vegetation type the northern part of the study area (Figure 4.3a), and occur on degraded former forest grounds. SOC stocks under woodlands are low since they are mainly retained on the poorer soils. For example, no woodlands remain on Vertisols or Gleysols. On other soils their SOC stock is close to the mean SOC stock of that soil type. The open structure of these forests, as described by Bennett et al. (1979) and pictured in Figure 6.2a, leaves the soil open for decomposition and explains the rather low SOC stocks, which are comparable to SOC under miombo forests described in literature (Walker & Desanker, 2004). Human-induced degradation such as removal of firewood and burning of the undergrowth could further inhibit accumulation of organic matter and thus soil carbon sequestration. However on Nitisols, woodlands have developed with a SOC stock of 120 $Mg.ha^{-1}$. Several woodlands in the Nitisol area have never been taken into agricultural use, since farmers considered these soils too difficult for handling for a long time (Bennett et al., 1979). This proves that if the natural vegetation had remained intact on some of the more fertile soils, they could have retained high levels of SOC.
Bushlands occur in many different forms: open to closed shrubland and thicket, sometimes with scattered trees. Many mixtures of these vegetation types are found. The vegetation of a fallow forest the first years after abandonment consists of a dense complex of shrubs and grasses with high organic matter inputs which are protected against decomposition (Figure 6.2b). Therefore the SOC stocks of young bushlands (<20 yrs) equal those of grasslands. Older bushlands have SOC stocks comparable to woodlands.

Figure 6.2 d, e and f show a typical sequence of bush clearing and planting of crops. Cassava is one of the main food crops and is grown on more than half of the fields in this study. When harvesting cassava roots for consumption, high amounts of soil are lost, implying also nutrient losses (Isabirye et al., 2007). The stem is kept aside for vegetative propagation while leaves and discarded stems are sometimes left in the field or sometimes used as domestic fuel (Isabirye et al., 2007). This results in almost no organic matter inputs (Figure 6.2g), a removal of nutrients during harvest and a bare soil pit prone to easy decomposition. As a result, SOC stocks are much lower than in other cropped fields. On the other hand, cassava is drought-resistant and tolerant of low fertility. Consequently cassava is the preferred crop on already poor, continuously cropped soils (Bennett et al., 1979).

On more fertile soils cultivation of other crops becomes more practicable (Bennett et al., 1979). For example on most Arenosols cassava is the only grown crops. However in some more fertile Luvic Arenosols on the coast recent established sisal and sesame fields were found, explaining the high C content of cropped fields on Arenosols. As can be seen in Figure 6.2f, interplanted agricultural fields without cassava can have a full soil coverage which inhibits decomposition. Organic inputs can be high as a result of crop remnants (e.g. maize stems) in different periods of the year from different crops and gradual breakdown of tree stems and other forest remnants. Therefore the preferential use of more fertile soils, as well as the vegetational characteristics of interplanted agricultural fields, explain the higher SOC stocks of other crops compared to cassava.
On average, homestead gardens (Figure 6.2l) had the highest SOC stocks. This is on the one hand the result of the input of animal manure, but on the other hand a result of selecting the best soils, often close to the river, for these gardens. Indeed, the mean value is highly influenced by some high SOC stocks found in gardens on Vertisols and Phaeozems. On poorer soils, the difference with other land uses is not so obvious, for example on Alisols, Lixisols and Acrisols it is equal to SOC stocks under other crops.

Grasslands and rice (which is also a member of the Poaceae or True Grasses) (Figure 6.2 c and k) have the second highest SOC stocks. It has been mentioned in literature that grasslands could maintain SOC levels equal to forests as the result of a good incorporation of SOC in the soil through grass roots. However, grasslands and rice are also mainly grown on the most fertile soils. On these soils, their SOC stocks are comparable to those of bushland, although standard deviations are very high due to a large variability and few samples.

Planting of cashew strongly reduces SOC. Weeds are considered a major problem because they conceal fallen nuts and constitute a fire hazard, thus intensive weeding is common practice (Ngatunga, 2001). Thus accumulation of organic matter is restrained and on the bare unprotected soil (Figure 6.2h) decomposition is enhanced. Agroforestry systems of cashew trees interplanted with crops (Figure 6.2i) perform better than bare cashew fields at young age (<20 yrs). However since crops are grown only in open spaces between trees (Ngatunga, 2001), they have less impact as trees grow older and bigger, and therefore older intercropped fields have no better SOC stock than plain cashew groves.

From the differences between land uses on one soil type it can be concluded that Phaeozems and Umbrisols are most sensitive to land use changes. On these soils, SOC stocks under bushland can become very large but they are easily lost after conversion to tree crops or cassava. In the clayey soils, Nitisols and Gleysols are more susceptible to changes than Vertisols, where SOC stocks always remain high (92 $Mg.ha^{-1}$ or more). Ferralic/Arenic Phaeozems can have some high SOC values under bushland, but SOC under the other land uses is not more variable than on soils with an argic horizon or Ferralsols. Arenosols always have very low SOC stocks, except for some cropped fields on Luvic Arenosols in the coastal area. The sensitivity of Phaeozems and Gleysols results in very high losses in SOC between 1997 and 2005, relative to their area.

## 6.6 Conclusions

The average SOC stocks in the study area are 73 $Mg.ha^{-1}$, which is comparable to other studies in Eastern Africa. The soils that can store the highest amounts of SOC in the study area are Vertisols, Phaeozems, Umbrisols and Nitisols (average SOC stock of 106 $Mg.ha^{-1}$). Although they cover less than 40% of the total area, they contribute almost 60% of the total SOC stock in 2005. However, they also contributed up to 50% of the total SOC loss due to land use changes between 1997 and 2005. This can be mainly attributed to the loamy Phaeozems and Umbrisols, which have a high SOC content in their A-horizon but which offer no protection in organo-mineral complexes such as in clayey soils. After land use change, SOC is easily lost from these soils. Alisols, Acrisols, Lixisols, Ferralsols, Arenosols and Ferralic/Arenic Phaeozems have significantly lower SOC stocks (average of 87 $Mg.ha^{-1}$). SOC stocks of Gleysols are intermediate at 87 $Mg.ha^{-1}$, which is mainly the result of the impeded growth of bushlands on these soils.

Remnants of closed forest, woodlands and bushlands of more than 20 years have SOC stocks between 66 and 70 $Mg.ha^{-1}$. Although this is low for forests in general, figures are comparable to SOC stocks under woodland found in literature. The low SOC stocks can be attributed to the retaining of natural vegetation on the poorest soils, to the open structure of the vegetation with often little groundcover and to the

disturbances by humans and fire. However, if woodlands are preserved on fertile soils they can have high SOC stocks, for example 120 Mg.ha$^{-1}$ on Nitisols.

The traditional cropping system, consisting in several years of cultivation followed by several years of bush fallow, is able to maintain high SOC stocks. The young bushland vegetation, with a complex mixture of grasses, shrubs and young trees, has an average SOC stock of 120 Mg.ha$^{-1}$. The same trend was observed by Swaine & Hall (1983) who reported substantially higher SOC stocks after four years of fallow (83.3 Mg ha$^{-1}$) than in natural forest (63.5 Mg ha$^{-1}$) in humid forests in Ghana.

After clearing, fields are established on the fertile grounds and have an average SOC stock of 98 Mg.ha$^{-1}$ (cropped fields without cassava). However, more than half of these cropped fields (without cassava) are found on the most fertile soil types described above. On less fertile soils and when cropping becomes continuous, cassava becomes most important, since it is the most resistant crop. SOC stocks under cassava are more than halved (39 Mg.ha$^{-1}$) than under other crops. Shortening of the fallow period has been observed for a long time (Bennett et al., 1979). If the fallow system is abandoned completely and converted to permanent agriculture with cashew or other crops, this will have serious implications on the SOC stocks.

Another threat for the regional SOC stocks is the expansion of cashew plantations, which in 2005 already cover 33% of the study area. After cassava, tree crops have the second lowest average SOC stock (50 Mg.ha$^{-1}$) which is the result of the removal of grass, undergrowth and litter by farmers to facilitate harvesting of cashew seeds. Planting other crops between the young trees (<20 yr) enhances the mean SOC stocks (to 79 Mg.ha$^{-1}$) but after 20 years this effect completely disappears, since crops can only be grown in the small spaces that remain between the old trees.

Grasslands, rice fields and homestead gardens are less common land uses, which occur mostly on the fertile soils and which have among the highest SOC stocks (mean total values between 114 and 128 Mg.ha$^{-1}$).

Total SOC stocks of the study area were estimated at 34.50 Tg in 1997. This decreased by 14% due to land use changes in 8 years time (to 2005).

It can be concluded that intensification of the agricultural system by reducing the fallow period and planting mainly cassava on the depleted soils as well as the large expansion of the cashew monocultures have caused a serious loss of SOC from the study area. Restoration of the traditional fallow system, intercropping of cashew trees with crops on a substantial area of the field, also after 20 years, and reforestation could be used to restore SOC stocks.

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# 7 Spatial Structures of Soil Organic Carbon

*Based on: Rossi, J., Govaerts, A., De Vos, B., Verbist, B., Vervoort, A., Poesen, J., Muys, B., Deckers, J., 2009. Spatial structures of soil organic carbon in tropical forests – a case study of Southeastern Tanzania. Catena, 77: 19-27.*

# 7.1 Introduction

In the previous chapter aforestation/reforestation was proposed as one of the solutions to revert SOC losses on degraded soils. Aforestation and reforestation projects are supported by local institutions (Topper & Kasuga, 2003) and can be funded by the Clean Development Mechanism (CDM) of the Kyoto Protocol. However, the Protocol limits reporting of C sequestration activities to those that are both "measurable and verifiable". Even if allowed as part of an accounting system, credit for C sequestration activities could be withdrawn if high standards of measurement cannot be met (UNFCCC, 2007). The feasibility and sustainability of C credit schemes will depend on appropriate measuring and monitoring schemes which are rapid, feasible and cost-effective.

Reliable measurements of SOC content are hard to get and labour-intensive due to the substantial spatial variability. Soil C stocks are influenced by climate, vegetation, soil physical characteristics and historical land use (up to more than 30 years before present) all of which vary spatially (Conant & Paustian, 2002; Conant et al., 2003). This is especially the case in forest soils, as a result of the heterogeneous nature of vegetation, microclimate and soil physical properties (Saetre, 1999). The IPCC (2000) states that adopted sampling techniques should be used that take into account spatial variability. A good knowledge of the soil C stock and its spatial variation leads to a sampling strategy that is balanced between reliability and cost-effectiveness, in agreement with the error that is allowed for the purpose of the study.

Factors to take into account are sample size and sample density in relation to the spatial scale of the variation. Sampling intervals can be optimized for soil mapping and for calculating average values by application of classical and geostatistical theories (Van Meirvenne, 1991). Several studies described SOC spatial variability using geostatistics in agricultural soils (Liu et al., 2006) or grasslands (Schloeder et al., 2001; Cerri et al., 2004). Similar studies on forest soils only focused on temperate regions (Bengston et al., 2007; Kirwan et al., 2005). In tropical forest soils geostatistic analyses were merely used to determine spatial dependence scales (Oake-Anti & Ogoe, 2006; Wang et al., 2002), but these results were not used to develop sampling strategies.

The aim of this chapter is to contribute to a better knowledge of the spatial distribution of soil C in tropical natural and plantation forest. Specific objectives are to identify the most cost-effective sampling technique for measuring SOC in different forests in southeastern Tanzania. This chapter presents a practical method for optimizing the sampling strategy for SOC. It provides a tool for reliable and cost-effective estimation of average C stocks and creation of C maps based on a chosen forest type and predefined precision.
A sampling strategy is proposed for 5 forest types. This design can be directly used in similar forests in the area; or it can be used as a guideline to set up new sampling schemes in different forests in a different environment.

# 7.2 Materials and methods

## 7.2.1. Selection of study sites

Five study sites of 144 ha each were selected in the most common forest/woodland/plantation types of the study area (Table 7.1 and Figure 7.1). Since the Rondo plateau has the highest forest cover, four forest sites were located close to Rondo village (see Figure 2.1). Starting from 1952 the Rondo forest Project set up plantations of hardwoods, pine, iroko (*Milicia excelsa* (Welw.) C.C. Berg) and teak (Clarke, 1995). The cashew site was selected on the lower Makonde Plateau close to Naliendele village (Figure 2.1) since cashew cannot grow at high elevations. Soils are very much alike in view of their comparable geological origin. They have a texture of loamy sand in the upper part and sandy loam in the argic horizon, a low base saturation and a low CEC (cation exchange capacity). Only under the teak plantation an Alisol, with higher CEC, could be found. The four sites on the Rondo plateau were located very close to each other; therefore slight differences in soil type were probably the result of the influence of different vegetation. Total SOC densities (0-1m depth) vary between 22.56 (cashew plantation) and 79.45 Mg $ha^{-1}$ (coastal forest).

***Table 7.1 Forest type, main tree species, location, elevation, average rainfall, year and way of establishment, soil type (determined using WRB; FAO, 2006), thickness of litter layer (samples were taken in 2 frames of 50x50cm) and total SOC densities (till 1m depth, calculated from 2 profile pits per forest).***

| Forest type | Tree sp. | Location | Elevation (m asl) | Rain[b] (mm $yr^{-1}$) | Established | Soil type | Litter (g $m^{-2}$) | $SOC_{0-1\,m}$ (Mg $ha^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| **Coastal dry forest** | *Albizia spp.*[a] | Rondo plateau | 850 | 1088 | ∞ | Acric Umbric Ferralsol | 1400 | 79.45 |
| **Miombo woodland** | *Brachystegia spp.*[a] | Rondo plateau | 800 | 1088 | ∞ | Acric Umbric Ferralsol | 600 | 72.47 |
| **Common teak plantation** | *Tectona grandis* Linn.f. | Rondo plateau | 850 | 1088 | 1967 - on cleared woodland | Umbric Alisol | 1400 | 57.88 |
| **Caribbean pine plantation** | *Pinus caribaea* Morelet | Rondo plateau | 850 | 1088 | 1967 - on cleared woodland | Acric Ferralsol | 2700 | 58.68 |
| **Cashew plantation** | *Anacardium occidentale* L. | Makonde plateau | 120 | 1137 | 1970 - on cleared woodland | Haplic Acrisol | 200 | 22.56 |

[a] Detailed vegetation composition by Clarke (1995)

[b] Rainfall data on Rondo (Clarke, 1995) and Makonde (Dondeyne et al., 2003).

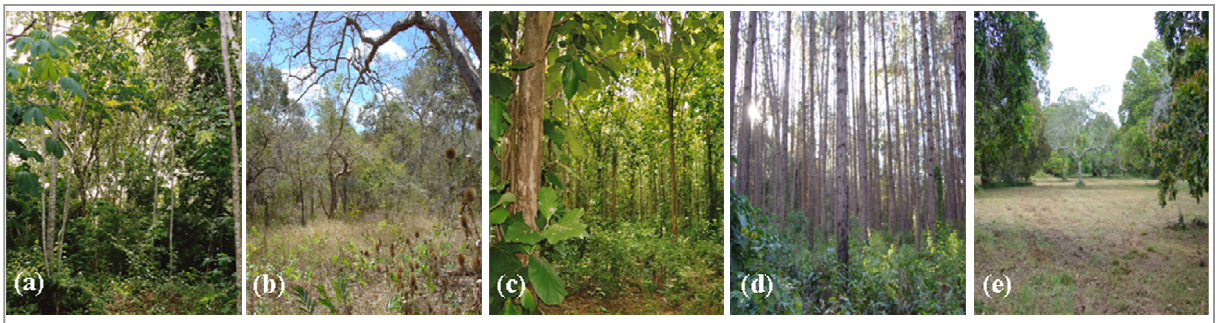



***Figure 7.1 The typical vegetation of the forests: (a) coastal forest, (b) miombo woodland, (c) teak plantation, (d) pine plantation and (e) cashew plantation.***

## 7.2.2. Field sampling strategy

Regular grid sampling can be insufficient since measuring variability depends on the spatial scale over which it is measured. Wide sampling intervals can cause all of the variance to appear as error while small intervals, chosen to resolve the short-range variance, make sampling of the whole area costly (Webster & Oliver, 2001). Therefore, a nested survey was chosen to identify the scale representing most of the variation. In each of the five selected forest sites, nine main centres were located roughly 400m apart. This wide interval was included in case that long-range spatial structures should be present. All other sampling points were placed at random orientations from these centres to comply with the random effects model and at different intervals, as recommended by Webster et al. (2006) (Figure 7.2). This resulted in 144 sample points per forest site. The particular merit of this design is to encompass most of the spatial variation and to ensure that the components of variance could be regarded as independent.

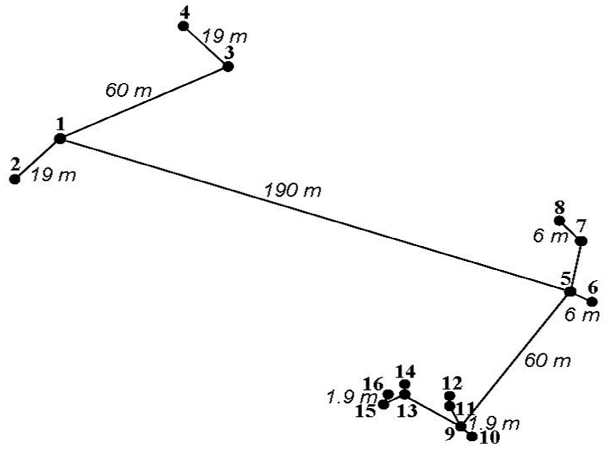



***Figure 7.2 Sampling strategy around one of the nine main nodes (1) in one forest. All other sampling points (2 to 16) were placed at random orientations from these centers covering a range of sampling intervals from 1.9m increasing in a geometric progression of approximately threefold increments to 190m. Economy was achieved by replicating only a proportion of the sampling centers at the shorter distances because their mean squares are estimated more precisely than those for the higher ones. Based on Webster et al., 2006.***

## 7.2.3. Soil sampling

Topsoil samples (0-5 cm) were taken, since the maximal spatial variation in organic C is expected in the surface layer of the soil (Siband, 1974; Mann, 1986; Detwiler et al., 1993; Walker & Desanker, 2004). Samples were taken using a ring sampler with a volume of 100 $cm^3$, dried in the oven for 48 hours at 105°C, weighed, sieved through a 2 mm sieve and mixed. Sample locations were recorded and the bulk

density (BD) was calculated. Organic matter content was determined on a 3g subsample with the loss-on-ignition (LOI) method and total organic carbon (TOC) was derived as described in Figure 5.3. Mass percentages (m%) as well as C densities (Mg.ha$^{-1}$, till 5 cm depth) were calculated. Carbon densities are indispensable for the assessment of C stocks and nutrient pools (De Vos et al., 2005; Tamminen & Starr, 1994) and it is the mandatory measuring unit for CDM accounting (UNFCCC, 2007).

## 7.2.4. Statistical analysis

Statistics (minimum, maximum, mean, standard deviation and coefficient of determination) summarize the data. Data of all fields were positively skewed; lognormal (ln) transformation resulted in a normal distribution. For the logarithmic distribution, mean (m) and standard deviation (s) could be calculated as described as follows (Aitchison & Brown, 1957):

$$m = \exp\left(\mu_{\ln} + \frac{\sigma_{\ln}^2}{2}\right) \qquad \textbf{Equation 7.1}$$

$$s = \sqrt{\left\{\exp(2\mu_{\ln} + \sigma_{\ln}^2)\right\}\left\{\exp(\sigma_{\ln}^2) - 1\right\}} \qquad \textbf{Equation 7.2}$$

where $\mu_{\ln}$ and $\sigma_{\ln}$ are the mean and standard deviation of the ln transformed data.
After normalization the mean hardly changed, but the value of the standard deviation altered for all locations (Table 7.2 and Table 7.3). This emphasizes the risk of considering the distribution of this population to be normal and therefore statistical misinterpretation when adopting classical statistical tests. Therefore the normalized data were entered in Anova and Bonferroni tests to determine differences in total SOC of the different woodlands, using the SPSS software.

## 7.2.5. Geostatistical analysis

The local variation can be estimated with the construction of a semivariogram. This procedure is used to measure the degree of relatedness between adjacent sampling points in a spatial series. The semivariance $\gamma(h)$ is the variance of the differences between observations at adjacent sampling points which are *h* distance and multiples of *h* distances apart. Points that are near each other (closely related) will have a small semivariance, while widely separated points will have high semivariances, indicating unrelatedness. The graph showing the relationship between the semivariances and the distance is known as a semivariogram.
The semivariogram function is defined as : $\gamma(h) = \frac{1}{2n(h)}\sum_{j=1}^{n(h)}[x(j) - x(j+h)]^2$ **Equation 7.3**

where *x(j)* and *x(j+h)* form a pair of points separated by a distance h, of which there are n (Deutsch & Journel, 1992).

The variogram parameters (Figure 7.3) characterize the behaviour of the variable, as described by Webster & Oliver (2001). The sill is the total vertical scale of the variogram (nugget effect + component scale). The distance at which the semivariogram levels off is called the range; beyond that distance the sampling variables are not correlated: it is the maximum extension of the spatial correlation between measurements of the variable. The nugget is the positive intercept of the variogram with the ordinate and represents unexplained spatially dependent variation or purely random variance. It is the combination of the measurement errors and the small-scale variability. More important than the absolute nugget value is the

nugget to sill ratio, which defines the proportion of short-range variability that cannot be described by a geostatistical model. A small nugget/sill in combination with a large spatial correlation range usually indicates that higher accuracy can be achieved in mapping; it gives an idea for the usefulness of the model for the variable (Isaaks & Srivastava, 1989).
Semivariograms were created in Variowin 2.2 (Pannatier, 1996).

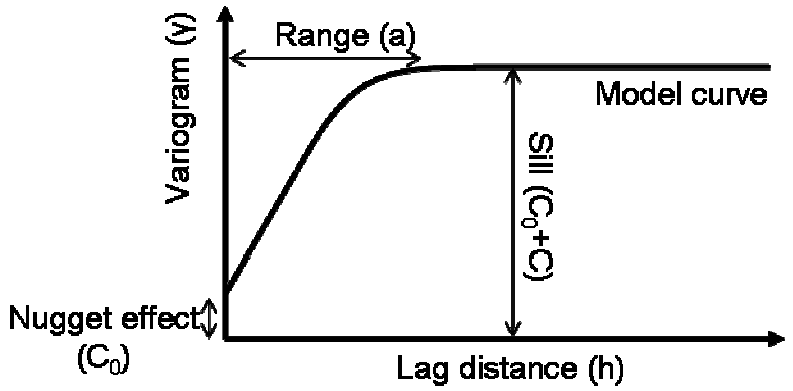



***Figure 7.3 A variogram model demonstrating the variogram parameters.***

## 7.2.6. Design of sampling strategy for a mean sampling value

In the classical sampling theory the number of samples (N) for measuring the average C content within one forest is calculated as follows (Motulsky, 1995):

$$N = \left( t_{\alpha} \frac{s}{precision} \right)^2 \approx 4.\left( \frac{s}{precision} \right)^2 \qquad \textit{Equation 7.4}$$

where the Student t value $t_{\alpha}$ is set at 2 (assuming n is large), s is the normalized standard deviation (Equation 7.2) and the precision is defined as the distance the 95% confidence interval extends on either side of the sample mean. Dividing this absolute precision (expressed in m% C or Mg $ha^{-1}$) by the total mean gives an idea of the relative precision.
Note that this method is only appropriate to measure one mean value at one moment. If it is necessary to look at the difference between two means, for example between two different fields or between the mean value of one field at different moment in time, the factor 4 is replaced by 8 in Equation 7.4 for the sample size of each of the two means.

Results can be further optimized using geostatistics. Since sample points within the variogram range are spatially correlated, sampling within the range will result in an overestimation of the variance and thus of the number of required samples (Van Meirvenne, 1991). If the variability is isotropic, the optimal sampling design for estimating the mean SOC stock is a grid with dimensions exceeding the range of spatial dependence (Van Meirvenne, 1991), if with such wide spacings enough samples can be taken.

## 7.2.7. Design of sampling strategy for predictive soil mapping

In the classical sampling theory, the predicted value of a soil property at any unvisited location is the typical mean value for the class. In geostatistics, the sampling interval required for predictive soil mapping can be estimated based on the maximum kriging estimation variance (McBratney et al., 1981; Saldaña et

al., 1998). In kriging the value of a measurement at an unobserved location is interpolated from observations of its value at nearby locations.

The best estimator of the value must have a minimum variance; this is the kriging variance $\sigma_k^2$. The maximum kriging variance will occur where the sampled data are furthest from the estimated location. So a criterion of a good sampling scheme is to minimize the maximum kriging variance, or its square root, the estimation error $\sigma_e$. Although the maximum distance between an interpolated point and its nearest sampling point can be minimized using an equilateral triangular grid, a square grid was preferred for reasons of convenience in indexing, site location, computer handling and travelling (McBratney et al., 1981). The program OSSFIM (Optimal Sampling Schemes for Isarithmic Mapping) developed by McBratney & Webster (1981) and implemented in Gstat by Pebesma & Wesseling (1998) was used to calculate the standard errors for individual observations and sample blocks at different sample intervals. As a result, a sampling scheme can be constructed in which the estimation error does not exceed a predefined value.

# 7.3 Results and analyses

## 7.3.1. Variability of soil C content between forests

General statistics of SOC concentrations and densities are shown in Table 7.2 and Table 7.3. Mean C densities (as well as C concentrations) in the 0-5 cm layer of coastal forest (13 Mg $ha^{-1}$) and teak plantation (12 Mg $ha^{-1}$) are significantly higher compared to the miombo woodland (9 Mg $ha^{-1}$), pine plantation (7 Mg $ha^{-1}$) and cashew plantation (5 Mg $ha^{-1}$). This is on average 16% of the SOC densities to 1m depth. The standard deviation for C densities is the highest in the natural forests (4 Mg $ha^{-1}$ in coastal forest; 3 Mg $ha^{-1}$ in miombo woodland) and lower in the teak, pine and cashew plantation (respectively 3, 2 and 1 Mg $ha^{-1}$). The coefficient of variation (CV) of C densities is between 3 and 10% smaller than the CV of C concentrations. CV's are very similar to those from other studies (Grigal et al., 1991).

***Table 7.2 Summary of general statistics of SOC concentrations (m%) at 0-5cm: number of samples N, minimum and maximum; mean, standard deviation s and coefficient of variation CV of the original dataset and normalized after the conversion (Equation 7.1 and 7.2). Mean values followed by the same letter are not significantly different (α =0.05).***

| | | | | Original data | | | Normalized data | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | Min (m%) | Max (m%) | Mean (m%) | s (m%) | CV (%) | Mean (m%) | s (m%) | CV (%) |
| **CF** | 134 | 0.85 | 5.78 | 2.53[a] | 1.01 | 40.05 | 2.53[a] | 1.07 | 42.22 |
| **MW** | 142 | 0.31 | 3.63 | 1.72[b] | 0.70 | 40.85 | 1.74[b] | 0.82 | 46.93 |
| **TP** | 132 | 1.04 | 3.82 | 2.44[a] | 0.60 | 24.43 | 2.45[a] | 0.63 | 25.59 |
| **PP** | 137 | 0.22 | 2.43 | 1.29[c] | 0.45 | 34.68 | 1.29[c] | 0.51 | 39.16 |
| **CP** | 136 | 0.39 | 1.62 | 0.86[d] | 0.26 | 30.38 | 0.86[d] | 0.26 | 30.19 |
| **Total** | 681 | 0.22 | 5.78 | 1.76 | 0.92 | 52.02 | 1.77 | 1.03 | 58.25 |

CF coastal forest, MW miombo woodland, TP teak plantation, PP pine plantation, CP cashew plantation

***Table 7.3 Summary of general statistics of SOC densities (Mg ha$^{-1}$) at 0-5 cm: number of samples n, minimum and maximum; mean, standard deviation s and coefficient of variation CV of the original dataset and normalized after the conversion (Equation 7.1 and 7.2). Mean values followed by the same letter are not significantly different (α=0.05).***

| | | | | Original data | | | Normalized data | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | Min (Mg ha$^{-1}$) | Max (Mg ha$^{-1}$) | Mean (Mg ha$^{-1}$) | s (Mg ha$^{-1}$) | CV (%) | Mean (Mg ha$^{-1}$) | s (Mg ha$^{-1}$) | CV (%) |
| **CF** | 134 | 5.24 | 24.08 | 12.59[a] | 4.05 | 32.18 | 12.61[a] | 4.25 | 33.73 |
| **MW** | 142 | 2.00 | 17.65 | 8.75[b] | 2.85 | 32.55 | 8.80[b] | 3.23 | 36.68 |
| **TP** | 132 | 6.59 | 19.18 | 11.85[a] | 2.67 | 22.51 | 11.86[a] | 2.75 | 23.16 |
| **PP** | 137 | 1.27 | 11.19 | 6.71[c] | 1.95 | 29.13 | 6.74[c] | 2.21 | 32.86 |
| **CP** | 136 | 2.51 | 8.51 | 4.87[d] | 1.20 | 24.64 | 4.87[d] | 1.22 | 25.05 |
| **Total** | 681 | 1.27 | 24.08 | 8.92 | 3.99 | 44.71 | 8.96 | 4.37 | 48.78 |

CF coastal forest, MW miombo woodland, TP teak plantation, PP pine plantation, CP cashew plantation

## 7.3.2. Classical sampling theory

The variation and therefore the number of samples required for calculating the mean C stock of the 0-5 cm layer with a predetermined precision (Equation 7.4) depends on the forest type but also on the way the C content is expressed (concentrations or densities). When measuring C concentrations, the sample size necessary to obtain an average value with a precision of 0.1 m% C is generally very high, especially when the variability is large, as can be seen in the two natural forest types (Table 7.4). Such numbers are often considered impractical. The sample size drops quickly when less precision is allowed. For example with an absolute precision of ± 0.30 m%C, 51 samples have to be taken in the coastal forest, compared to only 30 in the miombo woodland, 17 and 11 samples in teak and pine plantations respectively, and only 3 samples in the cashew plantation. The picture changes when C concentration is converted to carbon density. The

CV drops, as well as the number of samples which has to be taken. For example with a precision of ± 1.5 Mg ha$^{-1}$ which is, relative to the mean, comparable with the precision of 0.30 m%C described above, only 32 samples have to be taken in the coastal forest, 19 in miombo woodland and respectively 13, 9 and 3 in the teak, pine and cashew plantations.

***Table 7.4 Estimated number of samples (n) required for estimating the mean of SOC concentrations and densities with a certain level of absolute or relative precision (Equation 7.4) in the different forests (α=0.05).***

| | | | | | | |
|---|---|---|---|---|---|---|
| | 0.10 | 0.20 | 0.30 | 0.40 | 0.50 | Absolute precision (m%) |
| | 6 | 11 | 17 | 23 | 28 | Relative precision (%) |
| **Number of samples n (measured in C concentrations)** | 457 | 114 | 51 | 29 | 18 | *Coastal forest* |
| | 267 | 67 | 30 | 17 | 11 | *Miombo woodland* |
| | 157 | 39 | 17 | 10 | 6 | *Teak plantation* |
| | 103 | 26 | 11 | 6 | 4 | *Pine plantation* |
| | 27 | 7 | 3 | 2 | 1 | *Cashew plantation* |
| | 427 | 107 | 47 | 27 | 17 | *total* |
| | 0.50 | 1.00 | 1.50 | 2.00 | 2.50 | Absolute precision (m%) |
| | 6 | 11 | 17 | 22 | 28 | Relative precision (%) |
| **Number of samples n (measured in C densities)** | 289 | 72 | 32 | 18 | 12 | *Coastal forest* |
| | 167 | 42 | 19 | 10 | 7 | *Miombo woodland* |
| | 121 | 30 | 13 | 8 | 5 | *Teak plantation* |
| | 78 | 20 | 9 | 5 | 3 | *Pine plantation* |
| | 24 | 6 | 3 | 1 | 1 | *Cashew plantation* |
| | 306 | 76 | 34 | 19 | 12 | *total* |

## 7.3.3. Geostatistical approach

Variograms based on C concentrations displayed a more irregular behaviour; therefore variograms based on C densities were preferred. All variograms (Figure 7.4 and Table 7.5) were transitive, which means that they reach a sill value at which they level out. The variograms of coastal forest, miombo woodland, teak plantation and cashew plantation show a typical spatial behaviour (higher variation with increasing distance) and were described by a Spherical Model. The pine plantation shows no spatial structure at all: values are randomly distributed in the field and spatially independent of each other: this was described by the Nugget Effect Model. Variograms of all forests were isotropic: they are the same in all directions. Their sill approximately equals the variance of the observed data, implying that a finite variance does exist (Nielsen et al., 1973, Webster, 1985).

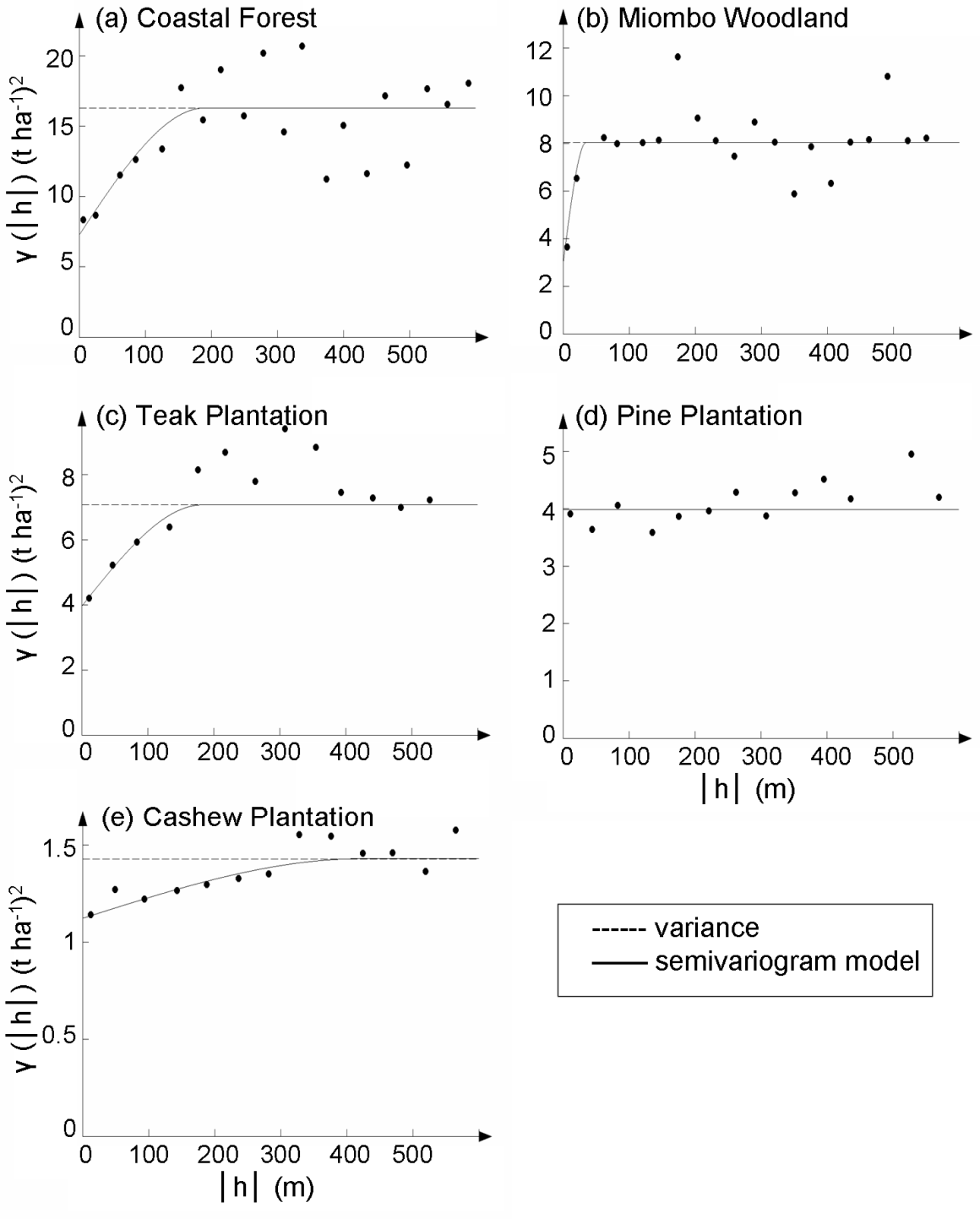



***Figure 7.4 Semivariograms of SOC densities of the 5 forests at 0-5cm.***

***Table 7.5 Summary of variogram properties: model, sill, range, nugget, nugget to sill ratio.***

| | Variogram properties | | | | |
|---|---|---|---|---|---|
| | Model | Sill $C_0 + C$ $(Mg\ ha^{-1})^2$ | Range a (m) | Nugget $C_0$ $(Mg\ ha^{-1})^2$ | Nugget/sill $C_0/C_0+C$ |
| **Coastal Forest** | Spherical | 16.4 | 191 | 7.3 | 0.45 |
| **Miombo woodland** | Spherical | 8.1 | 36 | 3.0 | 0.37 |
| **Teak plantation** | Spherical | 7.1 | 180 | 4.0 | 0.56 |
| **Pine plantation** | Nugget | 3.8 | ∞ | 3.8 | 1.00 |
| **Cashew plantation** | Spherical | 1.4 | 422 | 1.1 | 0.76 |

As described before, the natural coastal forest has the largest total variance and therefore the highest sill, while the cashew plantation sill is more than 10 times smaller. The natural coastal forest and the teak plantation have similar ranges of respectively 191m and 180m. These are about 5 times larger than the range of the miombo woodland. In the cashew plantation the sill is only reached after almost half a kilometre. The nugget varies from 1.1 in the cashew plantation to 7.3 $(Mg\ ha^{-1})^2$ in the coastal forest. It can be assumed that the measurement errors for all the plots are approximately equal, therefore the difference in nugget reflects the difference in variation that occurs at separation distances of less than the smallest sample spacing (here 1.9m). In the pine plantation all variation is explained by the nugget effect. Distinctive classes of spatial dependence can be adopted based on the nugget to sill ratio, as presented by Cambardella et al. (1994). A strong spatial dependence within the data is defined by a nugget/sill ratio of less than 25%. A ratio between 25 and 75% (moderate spatial dependence) can be observed in the miombo woodland (37%), coastal forest (45%) and teak plantation (56%). The cashew plantation, with a ratio of 76%, has only a weak spatial structure and the pine plantation has no spatial structure.
Improving of the results of the classical sampling theory by using only spatially independent data could not be done because beyond the long ranges too few samples remained.

In order to obtain an optimal sampling strategy for soil C stock mapping the dimensions of a rectangular grid were determined as a function of the maximum kriging estimation error $\sigma_\varepsilon$. The sampling intervals required to estimate properties with a prescribed precision for point samples, blocks of 1 are and 1 ha can be obtained from Figure 7.5 for the different forest types. There is an apparent increase in the kriging error for very small grid spacings in Figure 7.5c, because the few points, from which estimates are made, are concentrated in the centres of the blocks (McBratney & Webster, 1981).

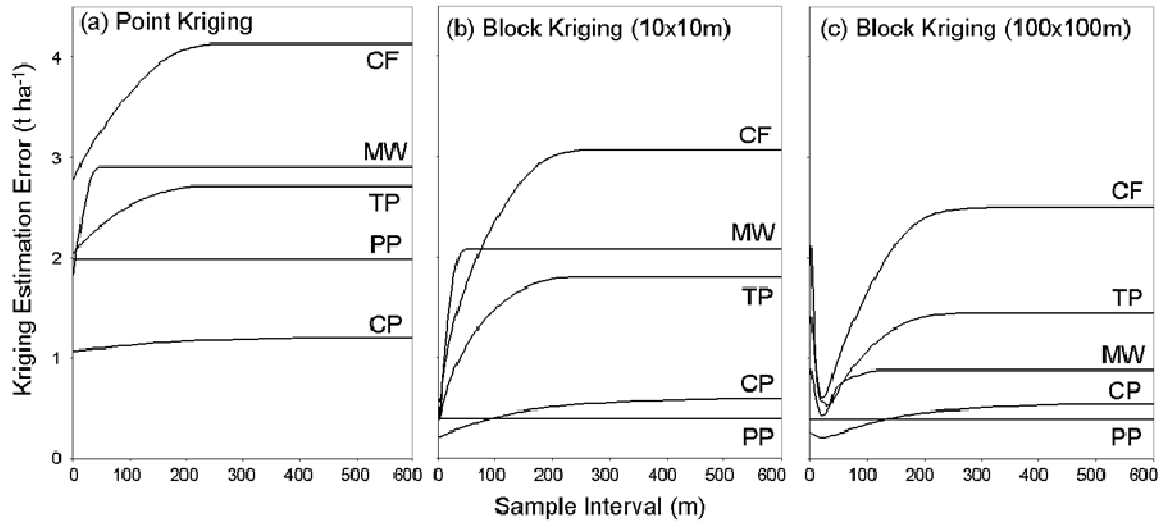



***Figure 7.5 Sampling intervals required for mapping C densities with a prescribed kriging estimation error $\sigma_\varepsilon$, for point and block kriging (CF coastal forest, MW miombo woodland, TP teak plantation, PP pine plantation, CP cashew plantation).***

# 7.4 Discussion

## 7.4.1. SOC concentrations (m%) or densities

The higher variability of C concentrations compared to C densities is remarkable. In these rich forest topsoil samples a relationship between BD and SOC does exist. Samples rich in SOM have proportionally lower total BDs due to the low specific density of organic matter compared to mineral compounds (De Vos et al., 2005) (Figure 7.6). This offsets high C concentrations since they are multiplied by BD for conversion to densities, decreasing the variability. A logical explanation is that C density describes the amount of C in a soil volume: 2 soil volumes with the same amount of SOC, which is the result of the same input of C

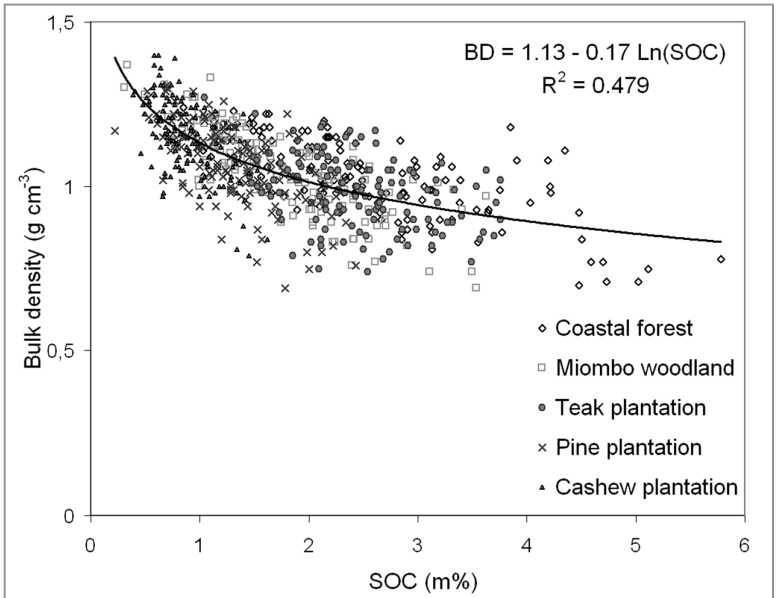



***Figure 7.6 A negative logarithmic relationship exists between the SOC concentration and bulk density (BD) at 0-5 cm samples of all the forests, which is probably the cause of the lower variability of C densities compared to C concentrations .***

into the soil, will have the same C density. Yet if the BD is not equal due to differences in soil texture or soil compaction, the C concentration can differ, resulting in a higher variation in C concentrations. This was also observed in the semivariograms, which were showing the spatial structures more clearly when depicted in C densities.
Although measuring BD, mandatory for C accounting through CDM (UNFCCC, 2007), can be time consuming, C accounting in densities gives less variable measurements of the field C stocks and less samples are necessary to estimate the mean.

### 7.4.2. Spatial structures of SOC within forests

Spatial heterogeneity of SOC reflects the interaction between pedological factors and vegetation dynamics. It was verified that parent material, climate and topography of all forests except the cashew plantation were uniform; therefore differences in spatial structure of SOC may be attributed to the influence of the occupying vegetation. Vegetation heterogeneity is seldom random but it exists as clusters or patches (Zahl, 1974). These patches are the result of abiotic and biotic processes: water, fire and wind as well as plant competitive processes of gap dynamics, herbivore and predator density, seed production, vegetation effects on microclimate and other (Holling, 1992). Once a site is put into production or otherwise disturbed, the spatial variability of the soil properties may be markedly altered. In mixed agricultural/forest landscapes human activities tend to reduce spatial heterogeneity (Krummel et al., 1987). The high total variance in the coastal forest is the result of the extremely variable vegetation composition and structure. In this natural forest the range of spatial dependence is 191m. The 38-year-old teak plantation, with closed tree canopy and dense herbal layer, has a spatial soil C allocation, which is in many ways comparable to the coastal forest. Mean soil C stocks are not significantly different. In a revision of 74 publications, Guo and Gifford (2002) show that broadleaf tree plantations placed onto prior native forest land first reduce C stocks by about 20%, but restore them when their age exceeds 40 years. This is an important finding to consider when planning reforestation activities. As a result of clearing and homogenization of the soil before planting, and little variation in vegetation type and structure, the nugget and total variance are approximately two times smaller than in the coastal forest. However, this variation can be found over the same distance: the teak plantation does not alter the size of the vegetation patches. The SOC stock of the pine plantation is almost half of the coastal forest stock. It has been demonstrated that planting of conifer trees reduces soil C stocks significantly (Guo & Gifford, 2002), because of changes in litter inputs, microbial diversity and activity, and the disturbance of soil during site preparation (Chen et al., 2004). Yet the litter layer in this forest is thicker than in the other forests (2.7 $kg.m^{-2}$). The pine trees have touching crowns, and the undergrowth consists of a dense herbal layer comparable to the teak plantation. However, opposite to the teak plantation, the pure nugget variogram shows that all values are independent of each other beyond the smallest sampling distance (1.9m). Probably the thick litter layer in this plantation diminishes all variability of SOC over the whole area. In the miombo woodland C stocks show a completely different spatial behaviour: the range is more than 5 times shorter than in the coastal forest. This can be explained by the typical vegetation dynamics of miombo woodland, which has a complex structure at shorter distances: on a scale of a few meters it is possible to discern different vegetation structures: closed forest, open grass areas and patches of burned ground. It is not surprising that the cashew plantation contains the lowest amount of SOC. A cashew plantation has an open structure and large open areas exist between the trees. Soil is exposed to direct sunlight which burns the C out of the soil. Moreover, the management will further inhibit soil C accumulation: before harvesting the ground

under the trees is cleared and all litter, cut grass and leaves are brushed away and burned. Thus biomass litter input into the soil becomes minimal and decomposition is stimulated. As a result variability has declined even more: the needed sample size of the cashew field is 10 times smaller than that of the natural coastal forest. The magnitude of the range has more than doubled relative to the coastal forest, implying that the variation is stretched out over a very large area. These results have important consequences for cost efficient planning of the sampling strategy.

### 7.4.3. Design of sampling strategy for a mean SOC value

The proposed sampling design includes an advice on sample size as well as sampling interval. Sample sizes to estimate mean C stocks can be obtained from Table 7.4. Sampling is optimized when samples are not autocorrelated. Therefore sample distances in the design should exceed the variogram range; which can be obtained from Table 7.5 for every forest. If no spatial structure can be observed, the anticipated number of samples can be arranged randomly.

For example the optimal strategy for measuring mean SOC stocks with a precision of 1 Mg $ha^{-1}$ is a regular grid with 72 samples at 191m distance or more for the coastal forest; 42 samples at 36m distance in the miombo woodland, 30 samples at 180m distance in the teak plantation, 20 randomly arranged samples in the pine plantation and 6 samples at 422 m distance in the cashew plantation. On average, the number of samples is divided by four if the measurements become half as precise.

### 7.4.4. Design of sampling strategy for predictive soil mapping

As can be seen in figure Figure 7.4a, small changes in kriging error for point estimates will lead to high differences in sampling distance. For example in the cashew plantation a $\sigma_\varepsilon$ of 1.2 Mg $ha^{-1}$ can be reached at 400m, but an 50m grid is required for a 1.1 Mg $ha^{-1}$ error. A $\sigma_\varepsilon$ of 2.1 Mg $ha^{-1}$ can be obtained at 10m for miombo woodland and teak plantation. Due to the short range of miombo woodland, $\sigma_\varepsilon$ will increase quickly and attain its maximum error of 2.9 Mg $ha^{-1}$ at 50m. At this distance $\sigma_\varepsilon$ is only 2.3 Mg $ha^{-1}$ in the teak plantation. In the coastal forest map the error can never be better than 2.8 Mg $ha^{-1}$ and reaches 4.1 Mg $ha^{-1}$ beyond 270m. In the homogeneous pine plantation, where no spatial correlation was observed within the field, geostatistics cannot improve the classical approach and its best soil map has an average C content attributed over the whole field.

Smaller errors can be obtained by increasing the pixel size of the map. When mapping blocks of 1 are (Figure 7.5b), errors of only 1 Mg $ha^{-1}$ or less can be reached at sampling distances of 15m for coastal forest, 10m for miombo woodland and 40m for pine plantations. The maximal kriging error in the cashew plantation is now 0.6 instead of 1.2 Mg $ha^{-1}$, which means that the other 0.6 Mg $ha^{-1}$ is explained by the within-block variance. When estimates of 1ha blocks would be needed, the variance within the block increases and kriging errors between blocks diminish further (Figure 7.5c). It can be concluded that kriging errors can be kept low by decreasing the sample interval or by increasing the block size.

### 7.4.5. Development of sampling strategies in other forests.

This study, based on a nested survey, gives an idea of the spatial scale of the variation of SOC in different forest types in the region. It can be used as a direct advice for sampling in similar forests in the region; or it can be used as a base for the development of new sampling strategies in other forests. Once the order of magnitude of the spatial variation is known, it is possible to estimate the variogram precisely by linear sampling with a sampling interval equal to half the correlation range identified in this study (Webster & Oliver, 2001). In case of natural forests and plantations such as the teak plantation, which have a closed canopy and complex undergrowth, this would mean sampling distances of about 90 m. In complex open woodland which is influenced by fires, such as the miombo woodland, a sampling distance of 18m is proposed. In cashew plantations, which are very homogeneous due to a yearly removal of the undergrowth, long sampling distances of 210m form a base. In a forest which has a homogeneous undergrowth and thick litter layer, such as the pine plantation, it can be assumed that no spatial structure exists and therefore no spatial variability study has to be conducted.
This regular sampling scheme can be used to calculate semivariograms before the actual start of the study. These results can be used to refine the sampling design to calculate mean values and for mapping in new forest types or in new regions, by following the same strategy as proposed in this chapter.

## 7.5 Conclusions

Cost-effective sampling strategies for estimating SOC under natural and plantation forests in southeastern Tanzania depend highly on the forest type, the scope of the research project and the measuring method. Volumetric sampling is strongly advised since it leads to a more cost efficient sampling strategy than measuring mass percentages.

In the 5 forest types of this study, SOC stocks in the upper 5 cm ranges between 5 (in the cashew plantation) and 13 (in the coastal forest) Mg $ha^{-1}$. Whereas CV's coincide with the CV's found in literature, variogram ranges and thus sampling distances tend to be very variable. Spatial structure of soil carbon has been reported between a few meters (Kirwan et al., 2005; Schloeder et al., 2001) to tens (Okae-Anti & Ogoe, 2005) or hundreds (Cerri et al., 2004) of meters. These differences were the result of mainly soil natural intrinsic variation, topography and cultivation practices. This chapter shows that the impact of vegetation structure only can cause a variation in ranges between tens and hundreds of meters. As a result, not only sample sizes but also sample intervals will be entirely different for various forest types. The optimal sampling distance for measuring mean SOC stocks varies between 36 m (in the patchy miombo woodland) and 422 m (in the homogenized cashew plantation); while in the pine plantation, which has no spatial structure, samples can be arranged randomly. Sample sizes fluctuate between 24 and 289 (0.5 Mg $ha^{-1}$ precision) and between 1 and 18 (2 Mg $ha^{-1}$ precision) for respectively cashew plantation and coastal forest. A rectangular grid with a sample interval of 25m can be used for SOC mapping with a point kriging estimation error of 3.0 Mg $ha^{-1}$ in the coastal forest, 2.6 Mg $ha^{-1}$ in miombo woodland, 2.2 Mg $ha^{-1}$ in the teak plantation and 1.1 Mg $ha^{-1}$ in the cashew plantation. At longer sample intervals the kriging estimation error increases quickly for the miombo woodland and more slowly for the forests with longer ranges. Block kriging strongly lowers the error. The pine plantation has no spatial structure and its best soil map has an average C content attributed over the whole field. When sampling new types of forests it is possible

to refine the sampling strategy based on a new spatial variability study. This can be based on a regular grid with sampling distances of half the range identified in this study.

This chapter proves that it is important to define research objectives, sampling precision and specific forest types before the start of the study and to adapt the sampling design. Using the same sampling strategy for all cases will result in oversampling and economic loss in homogeneous plantations such as cashew, and in unacceptable high error in coastal and miombo forests with a high variability. The sampling strategy for estimating the mean C stock is different from the strategy for soil C mapping based on points or blocks. If no spatial correlation can be seen, as in the pine forest, the mean value can be attributed to the whole field, therefore further sampling for soil mapping is a waste.

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# 8 Termites and Soil Organic Carbon

# 8.1 Introduction

In the previous chapter sampling strategies were developed for forests with different spatial structures as a result of vegetation induced patterns. However other factors could locally alter soil - and more specifically SOC - spatial heterogeneity. One such factor in the Tanzanian landscape is the presence of termites and their mounds. Numerous articles have discussed the influence of termites and termitaria on soil properties. Both increases and decreases in mound OC (organic carbon) levels have been observed, probably depending on termite species and activity status, soil type and land use. No information is yet available on the termite genera which occur in southeastern Tanzania, and how they specifically influence SOC on the different typical soils of the region. A characterization of the spatial patterns of SOC in and around termite mounds in a field would be necessary to adapt sampling strategies to these heterogeneities in the soil.

# 8.2 Literature review

## 8.2.1. General information on termites

Termites belong to the order of the *Isoptera* or 'equal wings' (*iso* = equal; *ptera* = wing) which refers to the adult primary reproductives possessing two pairs of equal length wings. The body plan or morphology of termites is rather simple indicating that they diverged very early in insect evolution from a generalized insect ancestor with gradual metamorphosis and the ability to fold the wings flat over the back. Termites are most closely related to cockroaches (*Blattaria*) but unrelated to true ants (*Hymenoptera*), although they are sometimes called 'white ants' (Eggleton & Tayasu, 2001).

Almost all species feed on dead plant material at different stages of decay (humification) (Bignell & Eggleton, 2000). Chemically, their food can be characterized as lignocellulosic matter. To facilitate breakdown and use of the food, complex relationships have evolved between termites and micro-organism (protozoa, bacteria and fungi) (Gillot, 2005).

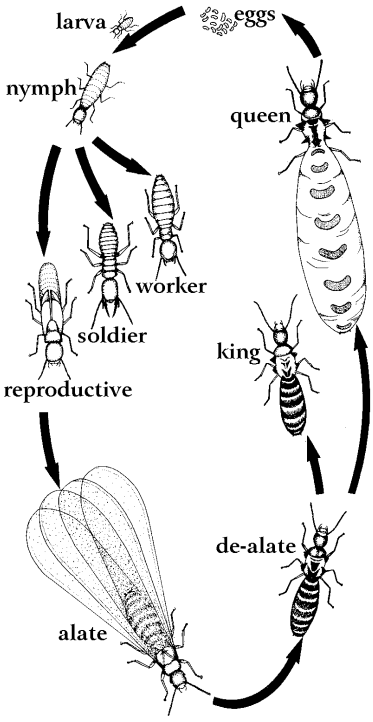



***Figure 8.1 Life cycle and caste system of termites (Hadlington, 1992).***

Termites are social insects, which exhibit brood care within their colony. Colonies are comprised of three basic castes (Figure 8.1): workers (sterile adults of both sexes), soldiers (also sterile adults of both sexes) and reproductives (primary and secondary). Worker termites undertake the labour of foraging, food storage, brood, nest maintenance, and some of the defence effort in certain species. The soldier caste has anatomical and behavioural specializations, providing strength and armour which are primarily useful against ant attack. The winged or alate caste

leaves the nest in large swarms, usually after the first good soaking rain of the rainy season, shedding their wings soon after landing at an acceptable site, where they mate and attempt to form a nest in damp timber or earth. The original royal pair may live for a considerable time (e.g. at least 17 years in *Mastotermes*) and, at maturity, a physogastric queen may produce up to 3000 eggs daily. Multiple pairs of kings and queens within a colony are not uncommon. In the lower termites several hundred or thousand numbers of individuals may be living in the colony, while in the higher termites it may be several million (Gillot, 2005).

Termites are the most diverse in the tropics, although they occur between the approximate latitudes of 30-45°N and 40-45°S (Lepage, 1983). Termites are a large and diverse group, comprising roughly 281 genera and over 2600 described species. At present, seven families and 14 subfamilies are recognized (Table 8.1) (Kambhampati & Eggleton, 2000). The composition of assemblages varies between ecosystems, through the action of historical, climatological, pedological and vegetational factors. Termite species composition in local species pools is constrained by the composition of regional pools, which in turn have been assembled by long term historical events (Eggleton, 1999).

Termites can be further categorised according to their feeding preference (Bignell & Eggleton, 2000). **Soil feeders** feed deliberately on mineral soil. Although the ingested material is highly heterogeneous, there are higher proportions of soil organic matter (SOM) and silica, and lower proportions of recognizable plant tissue than in other groups. **Soil/wood interface feeders** live on highly decayed wood which has become friable and soil-like or predominantly within soil under logs or soil plastered on the surface or inside of rotting logs or mixed with leaf litter in stilt-root complexes. **Wood feeders** take in wood and woody litter, including dead branches still attached to trees. **Litter-foragers** feed on leaves and small woody items, often taken back and stored temporarily in the nest. **Grass-feeders** forage for (usually dead dry) standing grass and other low vegetation stems, usually cutting and removing it to the nest. Minor feeding groups include termites feeding on fungi, algae and lichens on tree bark. Others are known to feed opportunistically on dung and vertebrate corpses. Some termites appear to feed on termite mounds built by other species. Some species fit into more than one group, especially under unfavourable conditions. A new feeding group classification was proposed by Donovan et al. (2001) who ranked species along gradient of less or more humified feeding material.
Termites can also be classified according to their nest structure (Bignell & Eggleton, 2000). A nest is defined as any colony centre, while mounds are substantial soil or carton structures, usually built on or in the ground. All termite species have identifiable nests where colony members are housed and protected. This varies from a loose association of connected galleries within the soil to huge and complex soil-built epigeal mounds more than 4-5m high. **Wood nesting** termites have colony centres which are normally within dead logs or standing trees. **Hypogeal nests** are below the ground, not associated with mounds. **Epigeal mounds** are built on the ground, free-standing or against the side of trees, usually well defined, highly complex and species-specific with a tendency to become more irregular as they age through erosion, additions and occupation by secondary inhabitants. Construction materials are generally subsoil, usually of relatively low organic content and carried in the mandibles without ingestion but with added salivary secretion to provide building material (e.g. *Macrotermes*, *Cornitermes*); carton, a mixture of faeces and macerated wood with a high lignin content (most wood-feeding termites), and faeces mixed with organic-rich topsoil (many soil-feeders, e.g. *Cubitermes*). **Arboreal mounds** are built in trees, and are usually made of carton.

## 8.2.2. Importance of termites

Termites may constitute as much as 10% of all animal biomass in the tropics (Wilson, 1993) and as much as 95% of soil insect biomass (Watt et al., 1997). Termite mound density can be very high, estimated for *Macrotermitinae* between 1 and 10 $ha^{-1}$ (Bouillon, 1970; Pomeroy, 1976, 1983). Soil brought to the surface in surface nests and sheathings may represent up to 2400 Mg $ha^{-1}$ and cover 10% of the soil surface (Meyer, 1960). In converting lignocellulosic biomass to insect biomass, termite production supports a large proportion of tropical vertebrate biodiversity, including many species of amphibians, reptiles, birds, and ground foraging insectivorous mammals (Wood & Sands, 1978).

Termites are capable of decomposing up to a third of annual grass, wood, and leaf litter within their habitat (Collins, 1981; Josens 1983) and subsequent humification and mineralization (Bignell & Eggleton, 2000). Termites (mainly *Macrotermitinae*) are estimated to consume 1 to 1.5 Mg of litter $ha^{-1}yr^{-1}$, roughly the amount consumed by wild or domestic grazers in dry tropical woodlands or wooded grasslands in East Africa (Lepage, 1981, Matsumoto & Abe, 1979). 90% of dead wood was found to be degraded by termites in a semi-arid savanna in Kenya (Buxton, 1981).

Together with earthworms, termites are considered 'ecosystem engineers' (Jones et al., 1994). At the heart of the soil engineering concept is the ability of these organism to move through the soil and to build organo-mineral structures with specific physical, chemical and microbiological properties (Lavelle et al., 1997) and therefore to be major determinants of soil structure, important conservators of fertility and even landscape architects (Lee & Foster, 1991; Stork & Eggleton, 1992). They alter ecosystem dynamics through the modification, maintenance and/or creation of habitats for other organisms in the ecosystem (Jouquet et al., 2006) and through modulating directly or indirectly the availability of resources to other species (Jones et al., 1994). Because their removal initiates a series of changes in the structural and functional integrity of the system (Paine, 1969), Jones (1990) considers that mound building, fungus growing termites function as the keystone taxon or dominant regulators of nutrient turnover in African dry woodlands. The role of termites as the dominant invertebrates in many tropical soils, with a wide sphere of influence (Brussaard et al., 1997) brings them into sharp focus in the current context of anthropogenic global changes (Brussaard et al., 1997, Freckman et al., 1997, Lavelle et al., 1997), especially land-use intensification (Giller, 1996; McNeeley, 1992, Swift, 1997, Woomer & Swift, 1994).

On the other hand various pest effects can reduce crop yields, e.g. grain losses from termite attack, reduced plant growth after termite attack or soil fertility or water availability restraints. Crop quality can also be affected by termite damage although indigenous African plant species are less susceptible to termite attacks (Black & Okwakol, 1997). Termites can cause considerable damage to timber, furniture, books and mud-bricks and termite mounds obstruct roads, houses and mechanized agriculture. In irrigated soils, flooded water can penetrate deep through pores and galleries made by termites, which can cause drought and erosion. Termites are also known producers of carbon dioxide ($CO_2$) and methane ($CH_4$) (Bignell et al., 1997) although some authors consider these gas fluxes small in the global context (Bignell et al., 1997; MacDonald et al., 1998, 1999; Eggleton et al., 1999; Jeeva et al., 1999; Sugimoto et al., 2000). Soil feeding termites have even been shown to reduce the net uptake of $CH_4$ by soils, presumably by partially offsetting bacterial oxidation of $CH_4$ with termite emissions of $CH_4$ (Macdonald et al., 1999).

***Table 8.1 Present classification of Isoptera (based on Kampbhampati & Eggleton, 2000 and Uys, 2002).***

| **Family**<br>**Subfamily**<br>**Group** | General information on feeding and nesting habits |
|---|---|
| **Mastotermitidae** | Monotypic Australian family nesting in ground in carton nests, feeding on dead wood and other dead plant material. |
| **Kalotermitidae** | Termites excavating systems of galleries in dead (dry) wood, mostly in dead branches of trees and shrubs. Occur throughout tropics and sub-tropics. Wood feeders. |
| **Termopsidae** | Building small to medium sized nests within dead (damp) wood. |
| **Termopsinae** | Termites nesting in large rotten logs in temperate and sub-tropical regions; wood feeders. |
| **Porotermitinae** | Eating sound and decayed dead wood. |
| **Stolotermitinae** | |
| **Hodotermitidae** | Termites nesting in the ground in arid parts of old world, foraging on the surface mainly for dry grasses. |
| **Termitidae** | |
| **Macrotermitinae** | Termites with a strong mutualistic relationship with the basidiomycete fungus *Termitomyce.* Nests are often subterranean, in mounds of other termites or in compacted soil mounds. Besides wood these termites eat leaf litter, herbivore dung, grass and saplings of tree crops. |
| **Apicotermitinae** | Soil feeding termites (a few general wood/soil interface, litter or detritus feeders) usually with amorphous underground nests. |
| **Nasusitermitinae** | Termites feeding on sound or decaying wood, herbivore dung, grass, leaf litter, bark, plant debris, soil and lichen; building hypogeal, epigeal and arboreal nests. Some species nest in wood and nests of other termites. |
| **Termitinae** | Termites with a range of feeding and nesting habits. |
| **Foraminitermes** | Soil feeding termites with hypogeal nests. |
| **Amitermes** | Generally wood (some wood-soil interface) feeding termites with hypogeal, epigeal or semi-arboreal nests or as secondary occupants within the nests of other species. |
| **Cubitermes** | Endemic African soil-feeding termites with hypogeal nests, large soil mounds, or as secondary occupants within the nests of other species. |
| **Termes** | Soil- and soil-wood interface-feeding termites with hypogeal, epigeal (*Dicuspiditermes*) or semi-arboreal (*Termes*) nests, commonly found as secondary occupants of other termites' nests. |
| **Serritermitidae** | Monotypic Brazilian family; lives in small chambers in external walls of *Cornitermes* nests. |
| **Rhinotermitidae** | Diverse group of wood- and soil nesting termites found throughout the tropics. Wood feeding. |
| **Psammotermitinae** | |
| **Termitogetoninae** | |
| **Rhinotermitinae** | |
| **Prorhinotermitinae** | |
| **Heterotermitinae** | |
| **Stylotermitinae** | |
| **Coptotermitinae** | |

## 8.2.3. Importance for soil

Besides climate, parent material, topography and time, living organisms are known as one of the soil forming factors. In the warmer latitudes, termites, together with ants and earthworms, are recognized as the most important group of soil fauna influencing soils physical structure and biological function. Termites can influence the soil properties in different ways: they can alter the soil profile development, soil physical properties, soil chemical properties and soil microbiology and have an impact on plant growth (Figure 8.2). These characteristics have been extensively discussed by Lobry de Bruyn & Conacher (1990) and by Holt & Lepage (2000).

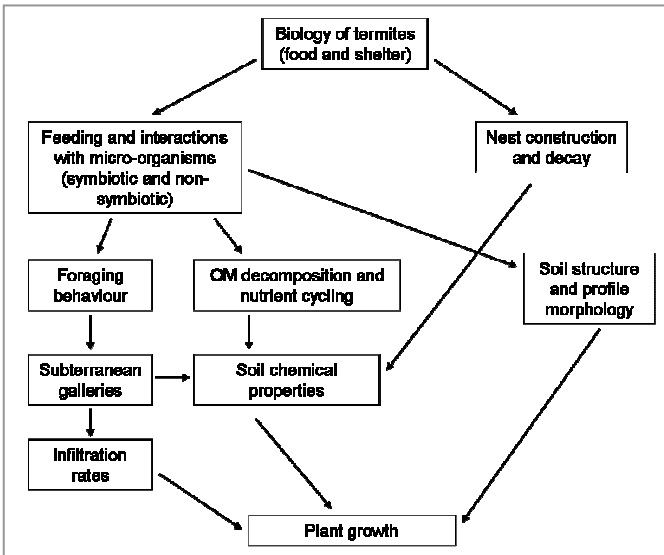



***Figure 8.2 Flow diagram showing interactions of termites and soil processes (Holt & Lepage, 2000).***

### *8.2.3.1. Soil profile development*

**Soil translocation and turnover:**

Termite activities such as mound building and the almost equally important (Lepage, 1974) construction of soil-covered runaways result in an accumulation and turnover of soil on the surface. The mass of soil contained in epigeal termite mounds together with estimates of mound erosion is often used to calculate soil turnover rates. Lobry de Bruyn & Conacher (1990) reported turnover rates varying between 0.02 and 4.7 Mg $ha^{-1}yr^{-1}$ and Aloni & Soyer (1987) calculated that over a period of 1000 years up to 37 cm of soil could be translocated by a population of humivorous mound-building termites in a southern Congo savanna. Subterranean termites can be equally significant as mound building termites in modifying soil properties (Wood & Sands, 1978).

**Soil texture and soil profiles:**

Authors have described termite induced 'soil mixing', or homogenization of the soil (Hole, 1961). On the other hand termite activities can result in the formation of texture layers (Nye, 1955; Watson, 1960), gradually textured soil profiles (Holt et al., 1980), profile inversions (Lee & Wood, 1971a) and stone lines (Williams, 1968; Folster, 1964). Micromorphological studies have concluded that the relic features of many tropical soils are a result of not only pronounced leaching over extended periods of time, but also of continuous disturbance and homogenization, principally through termite activity (Soyer, 1987; Stoops, 1989; Trapnell & Webster., 1986). It has been postulated that in the nests of fungus-growing termites, the proportion of clay is always more than in the bulk soil and often maximal in the royal cell and minimal in the outer wall (Jouquet et al, 2002). According to Donovan (1999), soil undergoes a physical fractionation as it passes through the termite gut rather than termites selecting a certain size fraction of the soil for ingesting. Nye (1955) regards the relative fertility of termite mounds as of minor account compared with the importance of the termites in forming a gravel free topsoil.

### 8.2.3.2. Soil physical changes

**Soil structure:**

Authors mentioned that termite mound soils had a higher aggregate stability and were less easily dispersed in water than adjacent soils (Pathak & Lehri 1959), although this is a function of feeding and mound-building strategies. The stability of soil aggregates against dispersion caused by wetting depends on organic matter, usually polysaccharides, and multivalent cations in the soil (Oades, 1984). Organic matter contained in termite mounds is often more polymerized than that of the nearby soil horizon and the higher organic matter and exchangeable cation content of the mound material result in high structural stability (Garnier-Sillam & Harry, 1995).

**Bulk density:**

Although it is well known that termites repack soil to form hard outer protective layers for their mounds, little information is available regarding the density of this material. It seems that termites may increase bulk density to a minor extent, probably by repacking the soil particles so that pore space is reduced; however, this may not be the case with all species (Lobry de Bruyn & Conacher, 1990). The increased hardness and lower porosity resulting from the higher bulk density together prevent seed lodgement and growth on the mounds of some species of termites (Holt & Lepage, 2000).

**Water infiltration and porosity (hydraulic conductivity):**

There are sometimes large discrepancies between the water holding capacities of termite mounds of different species. Garnier-Sillam & Tessier (1991) have shown that the work of termites can either provoke an increase of the total pore volume (certain humivorous species) or a considerable reduction in the pore volume (certain fungus-growing species). While compact structures reduce water infiltration, high porosity mounds have a high permeability. Disparities between mounds have been further attributed to the organic matter content of the mounds (Lobry de Bruyn & Conacher, 1990). Termites can increase infiltration and aeration by incorporating organic matter into the soil. Gallery systems associated with mounds, nests, and foraging territories of termite colonies are assumed to affect pore space, infiltration of water into the soil, aeration and the penetration of plant roots.

**Micropeds:**

Micropeds, produced either by faecal deposits or by mixing soil with saliva using the mandibles, are thought to have a significant influence on the soil micro-porosity, moisture storage capacity and infiltration rate (Kooyman & Onck, 1987).

**Sub-surface galleries:**

Soil profile morphology and most probably water movement are substantially influenced by the subterranean chambers and galleries, food storage chambers or fungus chambers. In some areas termite activity is thought to extend considerable distances below the soil surface (Holt & Lepage, 2000).

### 8.2.3.3. Soil chemical changes

Wood (1976) stated that in environments where the soil is inherently low in nutrients, termites might be important contributing factors to nutrient enrichment. As a consequence of a diet comprised entirely of

autotrophically fixed carbon, termites can exert a significant effect on carbon mineralization and nutrient recycling, especially where termite biomass is high, as in some tropical areas (Holt & Lepage, 2000). The input of organic matter and other nutrients to the soil environment can occur not only via faeces (Lee & Wood, 1971a), but also via salivary secretions, corpses and predators. In contrast to other soil animals, termites usually use their faeces for the construction of their nests and do not deposit them in the soil system where they would be available to microorganisms for recycling (Lobry de Bruyn & Conacher, 1990).

**Macro-nutrients:**

The nutrients most commonly studied in relation to the activities of ants and termites are calcium, magnesium, potassium and phosphorus. The input of organic matter and nutrients is stabilized in the nest structure when species select particles from clay rich horizons within the soils profile for the construction of their mounds. Mound material has also higher concentrations of exchangeable cations than adjacent soils (Lobry de Bruyn & Conacher, 1990).

**pH:**

Authors found both an increase (mostly with *Macrotermes* spp.) as a decrease in pH of termite-affected soils, while the majority of researchers have found no appreciable differences. A decrease in pH is associated with the incorporation of organic-rich excreta while an increase is often correlated with an increase in calcium (Lobry de Bruyn & Conacher, 1990).

**Inorganic N**

The organic nitrogen is slowly mineralized into inorganic forms such as $NH_4^+$ and $NO_3^-$, which are accessible by plant roots. Several studies have shown that the inorganic nitrogen levels of mound soil or of soil reworked by termites and placed on the soil surface as galleries or sheetings are much higher than those of nearby soils unaffected by termite activity (Holt & Lepage, 2000).

**Organic matter, organic C and organic N**

Organic matter contents vary and are influenced by feeding habits, but usually concentrations in the mound are 2-5 times higher than that of the surrounding surface soil (Holt & Lepage, 2000). Consequently organic C, total nitrogen and phosphorus are higher in mounds than in the surrounding soil (Lee & Wood, 1971a).

Differences in organic carbon accumulation are thought to be related to differences in feeding behaviour, selection of soil fractions and food processing (Holt et al., 1998). Black & Okwakol (1997) separated studies of termite soil nutrient enrichment by feeding types (grass, litter, polyphageous, soil and wood) and examined the relative enrichment ratios. Although differences between and within feeding types were noted, no consistent trend was apparent. Mounds of (mostly wood-feeding) *Macrotermitinae* are rarely enriched in OC and N when compared to nearby surface soils. They incorporate saliva rather than excrement into mound materials, which are in any case mostly constructed of subsoil, which tends to contain less C (Lobry de Bruyn & Conacher, 1990). Soil-feeders mainly use materials from the surface 10 cm of the soil for the construction of mounds. As this part of the soil profile has the highest organic content, the basic building material (faeces) contains more than 17% OM (Garnier-Sillam & Harry, 1995). Gut transit also seems to increase the stability of SOM by enhancing the formation of organo-mineral

complexes with the mineral component of the food, and further stabilization is to be expected from adsorption to the clay fraction of the mound. Garnier-Sillam & Tessier (1991) consider that the stabilization of organo-mineral complexes thus achieved is of major environmental significance, as it shifts soil C into long-turnover pools, with an overall benefit to the maintenance of fertility. Differences have been observed in OM content between soil and mound, which appear to depend on the initial level of OM in the soil (Anderson & Wood, 1984; Fall, 1998; Garnier-Sillam & Harry, 1995). In rich forest soils, no or slight differences were noticed, while significant increases were recorded for mounds built from poor savannah soils (Anderson & Wood, 1984).

Due to the removal of litter and other plant material, and thus the termite induced rapid turnover rates of organic material in the land use systems, OC contents of the surrounding topsoil are very low. Negative relationships between organic carbon, organic nitrogen and plant biomass and termite activity have been found by Veeresh & Belavadi (1986), Kalidas & Veeresh (1990) and others. Therefore, the adoption of innovative management options that help to stop or even reverse the decline in OC typically observed after cultivation of bush- or rangeland is of utmost importance (Bationo & Buerkert, 2001).

Termites also alter the C/N ratio. Lee & Wood (1971b) found that 28 out of 30 samples of termite-modified soil showed an increase in the C/N ratio compared with undisturbed soil. However, researchers in India and Africa have found contradictory results, indicating that the C/N ratio is either similar or lower in the termite mound compared with adjacent, unmodified soil (Shrinkhande & Pathak, 1948; Pomeroy, 1976). The difference in C/N ratios could be due to differences in mound construction, such as a reduced incorporation of faeces into the mound which may lead to a lower C/N ratio.

### 8.2.4. Influence of termite activities on vegetation

Most studies have found improved plant growth on, or in close proximity to, termite mounds and a vegetation comprising trees and shrubs that are quite distinct from that of the surrounding landscape (Arshad, 1982; Gutierrez & Whitford, 1987; Wood, 1996). Some of the factors suggested as contributing to the distinctive vegetation include protection from fire, improved drainage, greater soil depth, higher soil moisture and improved fertility status.

In Africa, termites can play a significant role in subsistence agriculture when termite mounds, with their nutrient enriched soils, are incorporated into traditional cropping systems (Mielke & Mielke, 1982; Nyamapfene, 1986). Studies carried out in Burkina Faso gave a clear indication of how the stimulation of termite activity by the use of mulch can lead to significant improvements in plant cover, plant species number, biomass production and rainfall use efficiency (Mando, 1997). Additional experiments using cowpea as a crop showed that there was a strong relationship between termite activity and crop nutrient uptake, crop performance and a change towards more beneficial soil physical properties (Mando, 1997, Mando & Miedema, 1997). Brouwer & Bouma (1997), in a synopsis of soil and crop growth research in the Sahel, concluded that termites can raise soil fertility, and that millet, cowpea, groundnut, and sorghum yields are all positively influenced around the sites of abandoned termite mounds. Conservation of indigenous termite faunas may therefore assist yield enhancement. Mound material may provide an alternative to mineral fertilisers (Bishosha Menea & Boloy, 1995) and farmers in Africa commonly spread termite mound soil in their fields to improve soil conditions and increase plant nutrient availability (Watson, 1977). In some situations, termites may have a significant negative effect on plant growth by feeding directly on root or above ground vegetative material (Wood, 1996).

### 8.2.5. Spatial heterogeneity

Through the impact of termites on different soil properties, termite constructions and especially mounds can be considered as 'islands' in ecosystems where the diversity and quantity of litter transformers, micro-predators and micro-organisms are often different from those in the surrounding soil and where nutrient release can be either enhanced or blocked depending on the age and composition of the structure (Lavelle et al., 1997). These patches in the landscape can be responsible for changes in morphology and performance of plants and the composition of plant communities (Salick et al., 1983; Darlington, 1989; Jouquet et al., 2004). The various direct and indirect interactions between termites and other above- and below-ground biota are powerful factors in creating spatial and temporal heterogeneity.

As sources of small-scale heterogeneity are increasingly seen to be vital in the maintenance of biodiversity (Huston, 1997; Vivian-Smith, 1997), soil engineers could play a key role in increasing plant species richness or modifying the plant-community structure of ecosystems. This spatial variability may also provide farmers with a 'least risk strategy' for crop production (Brinn, 1993; Brouwer et al., 1993). Earlier studies have noted the importance of canopy gaps, rotting logs, and topographical variation, but the soil quality heterogeneity introduced by soil-feeding termites may be at least as important (Fall et al., 2001).

Termites affect soil processes and heterogeneity at widely different scales, from fungus-comb chambers (scale of 1-100 $cm^2$, Abbadie & Lepage, 1989) to lenticular mounds (scale of 1-100 $m^2$, Abbadie et al., 1992; Konaté et al., 1999). While the influence of soil feeding termites is restricted to the surroundings of the mound, deeper soils and a wider zone around the construction (10–20 m) are subject to the influence of fungus growing termites (Wood, 1988).

### 8.2.6. Impact of land use changes on termites

Termite species and abundance depend on the vegetation type and land use. Gradients from arid and semi-arid ecosystems, through savannas and parklands to tropical forests are characterized by a gradual shift of dominance from wood- and litter-foraging species to soil-feeders. There is also an increase in the number of trophic groups present, probably reflecting the form and variety of organic matter inputs, plus the size of the humified organic matter pools present in the soil (Bignell & Eggleton, 2000).
Land use changes within a certain region will therefore have an effect on the composition of the termite community.
Forest and bush clearing have both direct and indirect effects on termites as disturbance removes vegetation, destroys nest sites, alters the soil environment and food sources and exposure to predators and parasites (Black & Okwakol, 1997). Termite abundance, biomass and species richness are generally reduced when forest is cleared (Collins, 1980; De Souza & Brown, 1994; Eggleton et al., 1996). Feeding group shifts are probably mostly due to changes in canopy cover, with concomitant effects on soil humidity (Eggleton et al., 1996). Annual crops generally severely deplete termite communities whereas tree plantations allow a better conservation of communities in terms of species richness and abundance (Lavelle et al., 2001). The method of clearing can also affect termite abundance and diversity: declines in termite diversity have been recorded after burning of savanna woodland and after tillage or mechanical clearing which destroy small epigeal mounds and shallow subterranean nests (Black & Okwakol, 1997). During moderate soil disturbances, modification of species composition is a more obvious consequence

than change in abundance or biomass, but heavy disturbance sharply reduces species diversity and abundance. The removal of organic residues and natural mulches which follows cultivation and conversion to permanent arable use selects residual species which can resist desiccation by deep nesting and feed on crop plants (Wood & Cowie, 1988), hence apparent termite activity can become high, while overall abundance and biomass decline (Wood, 1996). Wood (1996) has noted that termite species that become harmful to crops (arable or silvi-cultural) are invariably already present in the environment at sub-economic population levels and elevation to pest status normally results from changes (reductions) in the availability of natural foods (i.e. organic mulch) as long as the species concerned are able to withstand physical stresses (greater diurnal temperature fluctuations and periodic drought) associated with the intensification process. Lower termites, *Macrotermitinae* and wood-nesting *Termitidae* are more resilient to disturbance than soil-nesting groups (Gathorne-Hardy et al., 2000; Eggleton et al., 2002). Termite-mediated wood and litter decomposition would be unchanged under light and moderate disturbance intensity, whereas their soil conditioning might be compromised. This may have negative effects on agricultural productivity as there is accumulating evidence of the importance of soil-feeding termites for soil fertility (Donovan et al., 2001). Although farmers do not always deliberately destroy mounds, they fall victim to fires or dry out progressively during partial or complete forest clearance, with a disproportionately large effect on termite abundance and biomass (Eggleton et al., 2002). Soil-feeding species, which persist through the fallowing process into mixed food crop fields, are therefore more likely to be wholly subterranean (Eggleton et al., 2002). However there may be a lag between the onset of moderated disturbance and noticeable changes in assemblage composition as colonies can survive for a number of years after disturbance (Eggleton et al., 1996). This is probably one reason why the disappearance of soil invertebrate engineers is rarely acknowledged as a cause for soil physical degradation that occurs years or even decades afterwards (Lavelle et al., 2001). However field-scale changes in farming practices may have a wider impact at higher levels as changes in termite diversity can influence nutrient cycling, vegetation, atmospheric exchanges and energy fluxes at various scales and from diurnal intervals to long-term effects over hundreds of years (Black & Okwakol, 1997).

Environmentally friendly management practices should consider soil invertebrate engineers as a resource and properly manage it. The first requirement is to properly feed them to allow a significant amount of activity. There is evidence that all the practices that allow a significant return of plant residues to the soil maintain high levels of invertebrate activities. This is the case, e.g., for minimum tillage techniques that favour root production and the incorporation of dead root material to the soil; mulching, application of cow dung and other organic manures and wastes have similar effects (Lavelle et al., 2001). Jones et al. (2003) further recommend the use of reduced-impact logging techniques, maximizing forest patch size and connectivity, minimizing length of forest edges and leaving dead wood to decay in situ.

## 8.3 Problem definition

The prominent activity of termites in the landscape is known to induce a strong spatial heterogeneity in biotic and abiotic properties. Since all termite species somehow have an impact on the soil profile or on physical and chemical properties of soils, every inch of soil in areas occupied by termites has undergone some movement or altering. Although subterranean termites can be equally significant as mound building termites in modifying soil properties (Wood & Sands, 1978) and the construction of soil-covered

runaways is almost equally important as mound building for soil turnover (Lepage, 1974), termite mounds are most important in creating spatial heterogeneity in soil properties. Therefore the focus of this study will be on organic carbon stored in and around termitaria.
The spatial extent and the magnitude of SOC in and around mounds seem to be dependent on environmental factors and on the occurring termite species. When sampling soil properties such as SOC, this spatial heterogeneity has to be taken into account. Although OM concentrations in termite mounds are on average 2-5 times higher than that of the surrounding surface soil (Holt & Lepage, 2000), less than 10% of the soil surface is occupied by termitaria (Konaté, 1998). In random or regular sampling this effect might be overlooked and SOC stocks may be under- or overestimated.

The main question of this chapter is: how do different termite species influence SOC levels and distribution in different landscapes of southeastern Tanzania and how can SOC sampling integrate this spatial variability created by termites?

# 8.4 Methodology

## 8.4.1. Selection of the study sites

Three different locations were selected which included the most common soil types and landscape units of the region (Table 8.2). In each location 3 common land uses were chosen: natural vegetation, crops and a cashew grove. These plots were established at least 15 years ago, had a similar land use history, inclination and soil and contained a large amount of small and big termite mounds. A study site of 1 ha within each field was selected.

***Table 8.2 Characteristics of the 9 selected plots, in 3 locations.***

| **Location: Village (District)** | Land unit | Soil type | Texture topsoil & subsoil | Altitude | Selected fields |
|---|---|---|---|---|---|
| **Naliendele (Mtwara)** | Makonde Dissected Plateau | Arenic Acrisol | loamy sand to sandy clay loam | 120 m asl | 1. Cassava & pineapple<br>2. Bushland<br>3. Cashew |
| **Nachingwea (Nachingwea)** | Nachingwea Masasi Plains | Ferralic Acric Nitisol | sandy loam to heavy clay | 460 m asl | 1. Maize, cassava, pigeon pea, cowpea<br>2. Miombo woodland<br>3. Cashew |
| **Nanyanga (Tandahimba)** | Makonde Plateau | Acric Ferralsol | sandy clay loam to sandy clay | 900 m asl | 1. Cassava<br>2. Woodland-bushland<br>3. Cashew |

## 8.4.2. Sampling of termites richness

Termites are very patchily distributed, and they occur in a number of different microhabitats such as soil and surface litter, epigeal mounds, tree canopies, dead wood and tree-stumps and on the ground. Termites in the soil are often inconspicuous and may occur to considerable depth (Bignell & Eggleton, 2000).
Methods for species richness sampling often involve transects, as described by DeSouza & Brown (1994), Eggleton et al (1995) and Bignell & Eggleton (2000); and their ecological validity is argued in Jones & Eggleton (2000). In this study an adaptation of the transect method is applied where systematically 20 sections of 2x5m along 3 or 4 transects are selected in the plot. Each section is scanned for termites for a total of one person-hour with attention to following microhabitats: tree canopies (to a height of 2m above ground level), epigeal mounds, living wood, dead wood, soil within rotten wood, tree trunks and buttress roots, galleries on plants and trees, galleries on surface and litter, soil (till 40 cm depth in at least 10 excavations), surface litter, subterranean nests and subterranean galleries. This transect method has obvious advantages. It is rapid, avoids biases from sampling only in mounds and it is possible to train inexperienced collectors rapidly. Species richness is sampled more efficiently per unit of effort than methods designed to estimate abundance and biomass. Termites were sampled and stored in ethanol. Termite soldiers were preferred due to their importance in determination, but other castes were collected too.

Determination of the termites at genus level was based on the key of Bouillon & Mathot (1965, 1966).

## 8.4.3. Soil and termitaria sampling

Samples were taken from termitaria, reference micropits and reference profile pits. Per plot 30 reference micro-pits based on a regular grid were sampled at 0-5 and 40-45 cm using a ring sampler (volume of 100 $cm^3$). They were counted as a 'reference' soil sample if they were no traces of termite activity (such as soil-covered runaways, underground nests, …) were visible and if they were at least 5 m separated from the nearest mound. One reference profile pit was dug and samples were taken to 2m depth at regular intervals.

Termites belonging to the *Macrotermitinae* build large mounds with the nursery and fungus combs occupying a central section. It has been recommended by several authors to sample these different compartments (outer wall and nest structure) separately (Garnier-Sillam and Harry, 1995; Fall et al., 1999; Fall et al, 2001) reflecting possible different patterns of organic carbon dynamics within the mound. Two (if present) large mounds were sampled as can be seen in Figure 8.3a, taking into account the different sections of the mound. Additional samples were taken at the foot of the mound and at 2m distance, at 0-5 cm and 40-45 cm depth.
The structure of small mounds is usually quite different in that there is no fungus comb, or area of concentrated termite activity. The whole mound structure is essentially a honeycomb of galleries and food storage areas. Termite activity in such mounds is not restricted to the basal section and eggs and larvae can be found throughout the nest structure. 10 (if present) small mounds (<1m diameter) were sampled with a sample ring in the above and below ground part (Figure 8.3b). Soil samples were taken next to the mound and at 30 cm distance; at 0-5 cm and 40-45 cm depth.

Samples were dried in the oven for 48 hours at 105°C and weighed. Bulk densities were calculated by dividing the mass of the soil sample by the volume (100 $cm^3$). Samples sieved through a 2 mm sieve and mixed. Organic matter content was determined on a 3g subsample with the loss-on-ignition (LOI) method (overnight combustion at 550°C; Andrejko et al., 1983). Conversion to SOC was done using the equations of Figure 5.3.

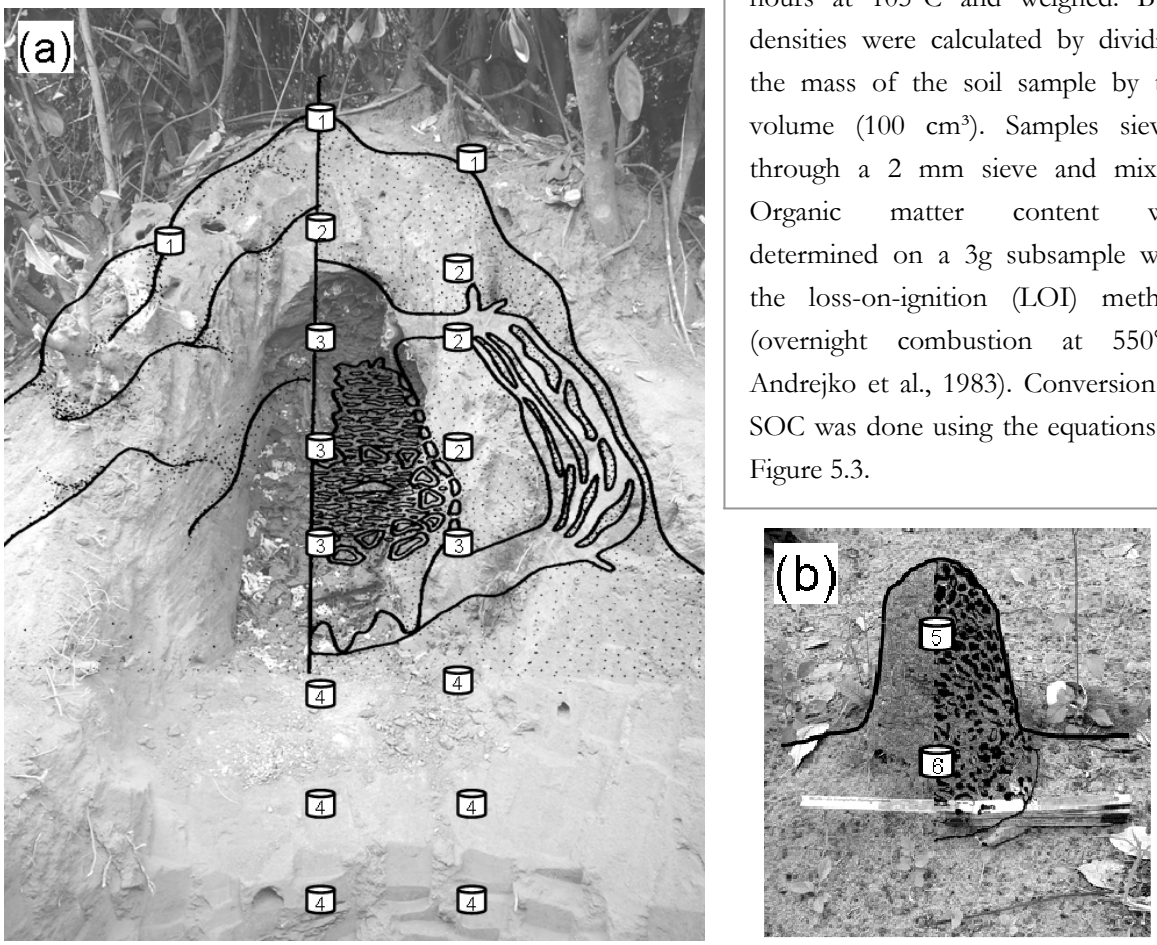



***Figure 8.3 Sampling strategy for a) large mounds. Ring samples (represented by cylinders) were taken at regular intervals (1) on top of the mound, (2) in the outer wall, (3) in the nest structure and (4) below the mound (till 2 m depth). b) In small mounds one sample was taken above ground (5) and one below ground (6).***

## 8.4.4. Data processing

### *8.4.4.1. Statistical tests*

All organic carbon data were first ln-transformed in order to obtain normality. ANOVA analysis (significance level of 0.05) tested significant differences of mounds and reference soils for all fields together, and for every field separately. Bulk density data were normally distributed and were not transformed. ANOVA testing of mounds and reference soil was carried out for all fields together and for every field separately. It has to be kept in mind that repeated reference samples were only taken at 0 and 40 cm depth. Deeper samples were only taken in 1 profile pit per field and can be used as a guideline for what happens at this depth, but its statistical value is less due to few repetitions.

#### 8.4.4.2. Calculation of SOC stocks in the field

Carbon densities were calculated for mounds and soil by multiplying OC, bulk density and volumes. The carbon stock in the reference situation – this is a field without mounds – is calculated by calculating and adding the carbon densities for the different horizons measured in the reference pits to 1m depth.
We estimated the volume of a large mound (above ground) by approximating the shape of the mound by a truncated cone, with a measured diameter, height and slope. The soil volume below large mounds which is also influenced by termites is averaged by a cylinder of 1m depth. Small mounds were approximated by a cylinder (above and below ground).
When considering the decrease in OC values next to the mound and at 0.3 or 2m distance (for large and small mounds respectively) to be linear, it is possible to calculate the sphere of influence around the mounds, or the radius at which the soil reaches the reference OC value. We calculated the depth of the termite influenced soil around mounds in the same way, by considering the decrease between 0 and 40 cm depth to be linear. Once these volumes are known, the carbon stock in the termite-influenced soil can be calculated. The carbon stock of the remaining uninfluenced volume of soil in the field was calculated according to the reference values.

# 8.5 Results

## 8.5.1. Termite diversity

The presence or absence of termite genera in the studied locations is indicated in table 3. In this study area in southeastern Tanzania, 35 termite genera from 5 families are found. All families except for the Australian *Mastotermitidae* and the Brazilian *Serritermitidae* are represented. *Termitidae,* with the soil feeding *Termitinae* subfamily among them, is the dominant termite family, as expected from literature (Kambhampati & Eggleton, 2000).
Termites from the ***Kalotermitidae*** and ***Termopsidae*** are found in all land uses. It has been discussed in the literature part that lower and wood-nesting termites are more resilient to land use changes. ***Hodotermitidae*** or harvester termites are mainly found in cropland. *Hodotermes* is a pest of pastures and cropping fields, especially those cultivated on virgin land since it prefers to colonise bare ground. *Microhodotermes* feeds mainly on small sticks and twigs (Uys, 2002). ***Macrotermitinae*** are known to be resilient to changes and are found in many fields. Genera known to attack crops are *Allodontermes*, *Macrotermes*, *Microtermes* and *Odototermes*, and these are abundantly found in cropped fields. ***Nasutermitinae*** nest underground and are therefore resistant to changes: they are found in all land uses (Uys, 2002). The most common species found in cropped fields are *Nasutitermes* and *Trinervitermes*, which are important pest species. ***Apicotermitinae*** are mostly soil feeders, which are sensible to land use changes and especially canopy loss. They appear mostly in forests and cashew groves. ***Termitinae*** are also soil feeding, moisture and shade dependent species. Therefore they are most abundant in forests and cashew plantations. *Amitermes* feeds largely on humus and decaying wood and is only found in forests and cashew groves. *Microcerotermes* is a very abundant pest species which attacks anything containing cellulose, from humus to sound dead wood (Uys, 2002). It is the only genus found in all the plots. ***Rhinotermitidae*** are subterranean wood-eating termites which need a constant source of moisture (Uys, 2002). They were only observed in forests.

***Table 8.3 Presence of termite species in the various locations and land uses.***

| **Family** | | Field location and land use | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Subfamily** | **Genus** | **Naliendele** | | | **Nachingwea** | | | **Nanyanga** | | |
| | | crop | forest | cashew | crop | forest | cashew | crop | forest | cashew |
| Kalotermitidae | Bifiditermes | | | | ✓ | | | | | |
| | Epicalotermes | | | | | | | | | ✓ |
| | Cryptotermes | | | | | ✓ | | | | ✓ |
| | Kalotermes | ✓ | | ✓ | ✓ | | ✓ | | ✓ | |
| Termopsidae | | | | | | | | | | |
| Stolotermitinae | Stolotermes | ✓ | | ✓ | | | | | | |
| Hodotermitidae | Hodotermes | | | | ✓ | | | ✓ | ✓ | |
| | Microhodotermes | | | | | | | ✓ | | |
| Termitidae | | | | | | | | | | |
| Macrotermitinae | Allodontermes | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | |
| | Ancistrotermes | ✓ | ✓ | ✓ | | ✓ | | | | |
| | Macrotermes | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | |
| | Microtermes | ✓ | ✓ | | | ✓ | | ✓ | ✓ | |
| | Odontotermes | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | |
| | Pseudacanthotermes | | ✓ | | | | ✓ | | | |
| Apicotermitinae | Apicotermes | | ✓ | | | ✓ | | ✓ | | ✓ |
| | Coxotermes | | | | | | ✓ | | | |
| Nasutitermitinae | Fulleritermes | | | | | | | ✓ | | |
| | Mimeutermes | | | | | | ✓ | | ✓ | |
| | Nasutitermes | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ |
| | Trinervitermes | | | | ✓ | ✓ | ✓ | ✓ | | |
| | Rhadinotermes | | | | | ✓ | | | | |
| Termitinae | Amitermes | | | | | ✓ | ✓ | | | ✓ |
| | Microcerotermes | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Basidentitermes | | ✓ | | | ✓ | | | ✓ | |
| | Batillitermes | ✓ | | | | | | | | ✓ |
| | Crenetermes | | | ✓ | | ✓ | | | | |
| | Cubitermes | | | | | | | | ✓ | ✓ |
| | Euchilotermes | | ✓ | ✓ | | | ✓ | | ✓ | ✓ |
| | Lepidotermes | | ✓ | | ✓ | | | | ✓ | |
| | Noditermes | | | | | | | | | ✓ |
| | Termes | | | | | | | | | ✓ |
| Rhinotermitinae | | | | | | | | | | |
| Rhinotermitinae | Schedorhinotermes | | ✓ | | | | | | ✓ | |
| Coptotermitinae | Coptotermes | | ✓ | | | | | | | |
| *Number of genera present* | | *9* | *14* | *8* | *9* | *14* | *12* | *9* | *12* | *11* |

Six mound building genera were found. *Macrotermes* is the most prominent genus with massive mounds of variable shape and size around a large centralised nest cavity filled with fungus comb. Mounds of *Odontotermes* are sometimes low and flattened while others are chimneys around air-shafts that descend into the soil. *Pseudacanthotermes* builds inconspicuous nests except for one species that makes one or more amorphous moundlets. *Cubitermes* makes small mushroom shaped, rounded or conical mounds and black or multi-hatted surface mounds sometimes appear on *Amitermes* nests. *Microhodotermes* builds sometimes a hard conical mound above the hive (Uys, 2002). Many mounds are deserted or inhabited by other than the original termite species. Therefore it is difficult to state which mound belongs to which genus of termite. However it can be concluded from the shape and appearance of the mounds that all large mounds (>1 m diameter) belong to wood-feeding species from the *Macrotermitinae* subfamily. Small mounds belong to the soil feeding *Termitinae* subfamily. In the text these will be further discussed as the large *Macrotermitinae* mounds (MM) and the small *Termitinae* mounds (TM).

## 8.5.2. OC in and around mounds

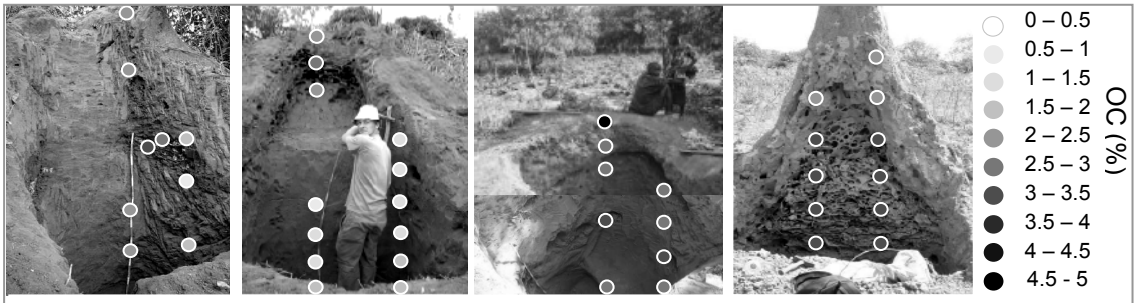



***Figure 8.4 Examples of OC (g C/100 g soil) in different parts of MM. Pictures are from Naliendele forest, Naliendele crop, Nanyanga crop and Nachingwea crop.***

The effect of heterogeneity of organic carbon within MM is illustrated with four examples in Figure 8.4. As expected from the literature review, it was observed that carbon concentrations are higher in the nest structures than in the outer wall. Sometimes raised OC levels were seen on top of the mound since it was enriched in OC as a result of the higher direct litter input and decomposition. Based on these observations MM were subdivided in several categories (Figure 8.1i).

Figure 8.5 summarises the distribution of SOC in and around MM and TM for all plots. A strong and significant increase in organic C is observed in the TM. The soil next to the mound is significantly enriched in organic carbon and at 30 cm the effect is noticeable but not significant. Although large MM have a visually large impact on the landscape, their actual influence on OC concentrations is limited. Only the central nest cavity and sometimes subterranean nests have significantly higher OC percentages than the reference. All other parts have non significant higher levels of C. On top of the mound organic material gathers which increases the OC slightly. Even between 1 and 2 m depth the soil is still influenced by termites and OC is higher than normal. The effect can also be noticed in the soil right next to the mound, but only slightly at 2m distance.

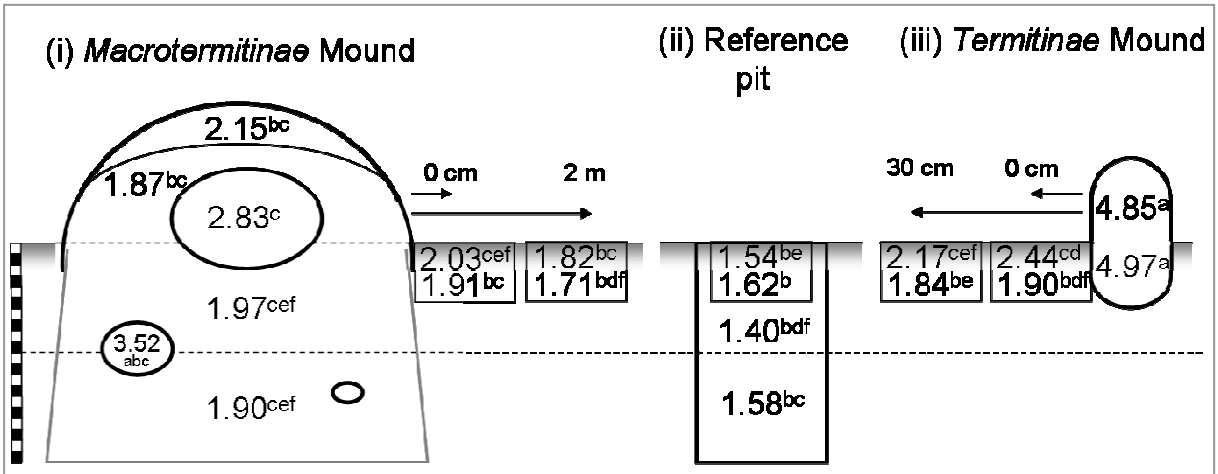



***Figure 8.5 OC levels (gC/100g soil) in and around mounds. Samples were taken: (i) in MM's: on top of the mound, in outer wall and main nest cavity, below the mound (0-1m depth), in smaller nests below ground, below the mound (1-2m depth), at the foot of the mound and at 2m distance of the mound (0 and 40 cm depth); (ii) in reference micro-pits at 0 cm and 40 cm and in 1 profile pit between 40 cm and 1m and between 1 and 2 m depth and (iii) at 30 cm and at the foot of TM's (0 and 40cm depth). Equal letters mean no significant difference (α=0.05).***

To estimate at which distance from the mound termites have no more influence, it was calculated where OC levels equal the reference soil. Based on the values of Figure 8.1, this is at 3.8m distance from the foot of the MM and at 1.2m distance from the TM. The vertical distance to which this influence extends is 0.8 m around the MM and 0.7 m around the TM.

The influence of termite mounds on OC in each field separately is presented in Table 8.4. For this overview landscapes are now divided in 13 classes: all samples from the aboveground and belowground part of the MM are grouped since they are not significantly different and soil samples at 0 and 40 cm are averaged.

The 3 fields in Naliendele, located on sandy Acrisols, have less than 1% OC in the reference pits, which is significantly lower than the other locations. Fields on the clayey Nitisols of Nachingwea have the highest C levels, especially in the subsoil. In Nachingwea C levels in the forest topsoil are significantly lower than in agricultural land. The forest is an old Miombo forest where all undergrowth is destroyed by regular fires. Rotations of pigeon pea, cassava, cowpea and maize are grown on the agricultural field. The soil here is covered with decomposing remnants of last year's maize stems, which probably causes the 4.13% of OC and high SD. Nanyanga is situated on Mollic Ferralsols. SOC is significantly higher in the forest than in the other fields.

SOC levels in the top-soils are generally low. This could be the result of surface litter removal and accelerated organic matter decomposition by the termites, thus impeding the build up of an organic horizon (Lepage, 1981; Collins, 1981; Arshad, 1982; Lee, 1982; Jones, 1989). This underlines the importance of treating the 'reference' samples with some caution. It is possible that the true reference soil, uninfluenced by termites, has different organic matter levels than the samples taken in the reference pits. However, this is very difficult to verify.

***Table 8.4 Mean organic carbon (gC/100g soil) per location and land use for: aboveground part of MM including the nests, soil below MM (0-2m depth), soil next (0m) to MM (average between 0 and 40 cm depth), soil at 2m distance from MM (0-40 cm depth), reference micro-pits (0-40 cm depth), reference pit (40cm-2m depth), aboveground part of TM, below ground part of TM, next to TM (0-40 cm depth) and at 30 cm distance of TM (0-40 cm depth). N= number of samples, SD = standard deviation. Equal letters mean no significant difference (α=0.05) within each field.***

| | | | Location | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Naliendele | | | Nachingwea | | | Nanyanga | | |
| | | Sample | N | Mean | SD | N | Mean | SD | N | Mean | SD |
| Land Use | Crop | *MM above* | 9 | $1.28^{b}$ | 0.33 | 13 | $2.94^{ab}$ | 0.42 | 11 | $1.84^{c}$ | 0.46 |
| | | *MM below* | 20 | $0.92^{bd}$ | 0.17 | 10 | $3.11^{ab}$ | 0.39 | 13 | $1.69^{c}$ | 0.12 |
| | | *MM 0m* | 8 | $0.94^{bd}$ | 0.18 | 8 | $2.86^{ab}$ | 0.40 | 6 | $1.54^{c}$ | 0.31 |
| | | *MM 2m* | 8 | $0.74^{cd}$ | 0.15 | 8 | $2.69^{ab}$ | 0.52 | 4 | $1.41^{c}$ | 0.26 |
| | | *Ref micro* | 73 | $0.61^{c}$ | 0.12 | 63 | $4.13^{a}$ | 2.25 | 53 | $1.16^{c}$ | 0.15 |
| | | *Ref deep* | 4 | $0.76^{bcd}$ | 0.12 | 5 | $1.92^{ab}$ | 0.31 | 7 | $1.19^{c}$ | 0.20 |
| | | *TM above* | 10 | $3.76^{a}$ | 0.50 | 5 | $3.57^{ab}$ | 2.32 | 10 | $10.93^{ab}$ | 8.16 |
| | | *TM below* | 10 | $3.66^{a}$ | 0.57 | 5 | $3.14^{ab}$ | 1.88 | 9 | $14.40^{a}$ | 7.32 |
| | | *TM 0m* | 20 | $0.84^{d}$ | 0.33 | 20 | $2.65^{ab}$ | 1.69 | 19 | $5.70^{b}$ | 2.07 |
| | | *TM 0.3m* | 20 | $0.75^{cd}$ | 0.26 | 10 | $1.40^{b}$ | 0.28 | 18 | $4.92^{c}$ | 3.15 |
| | Forest | *MM above* | 12 | $1.66^{b}$ | 0.32 | 12 | $2.82^{a}$ | 0.26 | 13 | $2.84^{b}$ | 0.50 |
| | | *MM below* | 12 | $1.02^{d}$ | 0.23 | 11 | $2.83^{ac}$ | 0.26 | 14 | $3.05^{b}$ | 0.34 |
| | | *MM 0m* | 10 | $1.06^{d}$ | 0.36 | 9 | $3.06^{ac}$ | 1.35 | 10 | $2.97^{b}$ | 0.28 |
| | | *MM 2m* | 10 | $0.95^{cd}$ | 0.22 | 8 | $2.08^{ab}$ | 0.79 | 12 | $2.68^{b}$ | 0.78 |
| | | *Ref micro* | 51 | $0.71^{c}$ | 0.15 | 58 | $1.06^{b}$ | 0.50 | 49 | $2.36^{b}$ | 0.87 |
| | | *Ref deep* | 5 | $0.92^{cd}$ | 0.28 | 2 | $2.44^{ab}$ | 0.20 | 5 | $2.09^{b}$ | 0.24 |
| | | *TM above* | 10 | $4.04^{a}$ | 0.73 | 11 | $4.37^{a}$ | 1.76 | 9 | $5.70^{a}$ | 0.85 |
| | | *TM below* | 10 | $3.84^{a}$ | 0.93 | 12 | $3.78^{ac}$ | 2.09 | 9 | $5.37^{a}$ | 0.80 |
| | | *TM 0m* | 20 | $1.37^{bd}$ | 0.58 | 25 | $1.70^{bc}$ | 1.07 | 18 | $3.10^{b}$ | 1.67 |
| | | *TM 0.3m* | - | - | - | 26 | $1.98^{b}$ | 3.61 | 19 | $2.54^{b}$ | 0.91 |
| | Cashew | *MM above* | 23 | $1.39^{b}$ | 0.25 | 11 | $2.18^{a}$ | 0.54 | 18 | $4.83^{a}$ | 3.45 |
| | | *MM below* | 13 | $1.10^{bd}$ | 0.17 | 11 | $2.60^{a}$ | 0.40 | 8 | $2.02^{b}$ | 0.25 |
| | | *MM 0m* | 8 | $1.06^{bef}$ | 0.25 | 8 | $2.26^{a}$ | 0.44 | 10 | $1.75^{b}$ | 0.19 |
| | | *MM 2m* | 11 | $0.73^{cdf}$ | 0.18 | 16 | $2.09^{a}$ | 0.50 | 12 | $2.00^{b}$ | 1.52 |
| | | *Ref micro* | 52 | $0.74^{ce}$ | 0.35 | 49 | $1.96^{a}$ | 0.55 | 37 | $1.41^{b}$ | 0.27 |
| | | *Ref deep* | 5 | $0.89^{bc}$ | 0.20 | 4 | $2.75^{a}$ | 0.14 | 3 | $1.37^{b}$ | 0.67 |
| | | *TM above* | 8 | $2.64^{a}$ | 1.31 | 10 | $2.49^{a}$ | 0.74 | 10 | $5.20^{a}$ | 0.59 |
| | | *TM below* | 8 | $2.59^{a}$ | 0.92 | 10 | $2.78^{a}$ | 1.41 | 10 | $5.02^{a}$ | 0.63 |
| | | *TM 0m* | 16 | $0.65^{c}$ | 0.15 | 19 | $2.02^{a}$ | 0.51 | 20 | $1.62^{b}$ | 0.50 |
| | | *TM 0.3m* | 16 | $0.60^{c}$ | 0.09 | 20 | $2.13^{a}$ | 0.49 | 19 | $1.43^{b}$ | 0.26 |

***Table 8.5 Significant differences of mean OC levels (gC/100g soil) between fields for reference and termitaria soils, Equal letters mean no significant difference (α=0.05) within each column.***

| Field | | Reference micropit | MM above | TM above & below |
|---|---|---|---|---|
| **Naliendele** | **Crop** | w | v | wx |
| | **Forest** | w | vx | wx |
| | **Cashew** | w | v | w |
| **Nachingwea** | **Crop** | v | wy | wx |
| | **Forest** | x | wz | wx |
| | **Cashew** | y | xyz | w |
| **Nanyanga** | **Crop** | xz | vz | v |
| | **Forest** | y | wz | vx |
| | **Cashew** | z | w | x |

A significant increase in OC is observed in all TM compared to the reference micro-pits, except for the agricultural and cashew field of Nachingwea, where SOC levels are already high. Levels are often raised by more than 3% OC. Within one location, no significant trend in OC levels of TM between different land uses was observed (Table 4b). However, they are significantly higher in Nanyanga than in the other locations. Although not so remarkable as small mounds, C levels in MM are between 0.22 and 3.42% higher than in the reference micro-pits (significant in 6 cases) in all fields except again Nachingwea agricultural field. SOC below the mounds is 0.31 to 1.77% higher than in the reference, being significant in 5 cases, except in Nanyanga agricultural field. Again, OC levels did not express a trend between land uses, but they did between locations, being significantly lower in Naliendele.

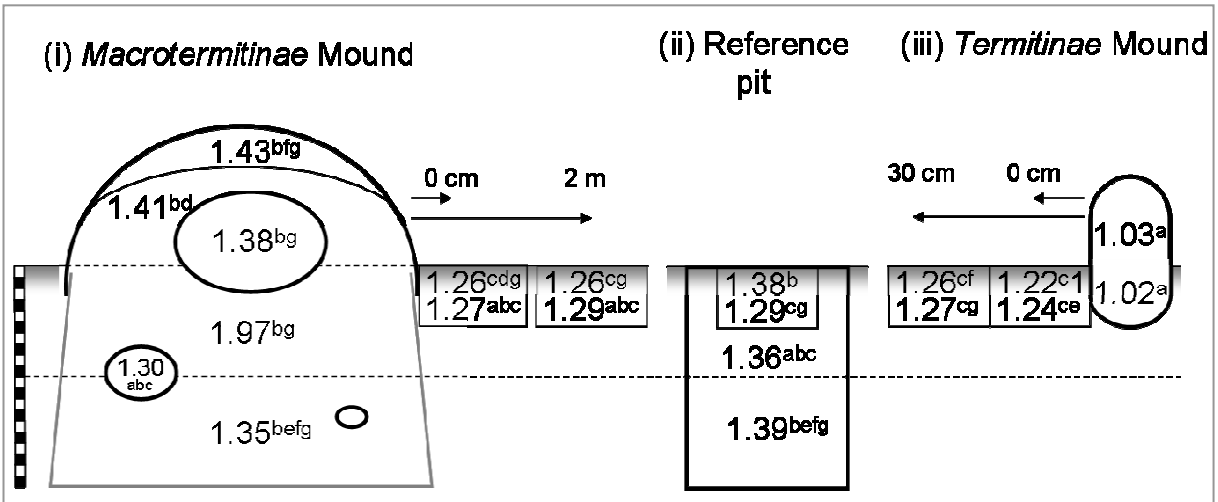



***Figure 8.6 Bulk densities (g/cm³ soil) in and around mounds. Samples were taken: (i) in MM's: on top of the mound, in outer wall and main nest cavity, below the mound (0-1m depth), in smaller nests below ground, below the mound (1-2m depth), at the foot of the mound and at 2m distance of the mound (0 and 40 cm depth); (ii) in reference micro-pits at 0 cm and 40 cm and in 1 profile pit between 40 cm and 1m and between 1 and 2 m depth and (iii) at 30 cm and at the foot of TM's (0 and 40cm depth). Equal letters mean no significant difference (α=0.05).***

## 8.5.3. Bulk density in and around mounds

***Table 8.6 Mean bulk density (g/cm³ soil) per location and land use for: aboveground part of MM including the nests, soil below MM (0-2m depth), soil next (0m) to MM (average between 0 and 40 cm depth), soil at 2m distance from MM (0-40 cm depth), reference micropits (0-40 cm depth), reference pit (40cm-2m depth), aboveground part of TM, below ground part of TM, next to TM (0-40 cm depth) and at 30 cm distance of TM (0-40 cm depth). N= number of samples, SD = standard deviation.***

| | | | Location | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Naliendele | | | Nachingwea | | | Nanyanga | | |
| | | Sample | N | Mean | SD. | N | Mean | SD | N | Mean | SD |
| Land Use | Crop | *MM above* | 9 | 1.42$^{cd}$ | 0.14 | 13 | 1.37$^{a}$ | 0.09 | 11 | 1.42$^{b}$ | 0.20 |
| | | *MM below* | 20 | 1.46$^{c}$ | 0.10 | 10 | 1.36$^{a}$ | 0.14 | 13 | 1.44$^{b}$ | 0.12 |
| | | *MM 0m* | 8 | 1.42$^{cd}$ | 0.09 | 8 | 1.20$^{a}$ | 0.15 | 6 | 1.42$^{b}$ | 0.13 |
| | | *MM 2m* | 8 | 1.45$^{cd}$ | 0.06 | 8 | 1.22$^{a}$ | 0.12 | 4 | 1.45$^{b}$ | 0.04 |
| | | *Ref micro* | 73 | 1.32$^{d}$ | 0.12 | 63 | 1.33$^{a}$ | 0.16 | 53 | 1.36$^{b}$ | 0.14 |
| | | *Ref deep* | 4 | 1.51$^{cd}$ | 0.09 | 5 | 1.45$^{a}$ | 0.13 | 7 | 1.32$^{b}$ | 0.13 |
| | | *TM above* | 10 | 0.94$^{a}$ | 0.17 | 5 | 1.15$^{a}$ | 0.22 | 10 | 0.87$^{a}$ | 0.09 |
| | | *TM below* | 10 | 0.86$^{a}$ | 0.16 | 5 | 1.13$^{a}$ | 0.27 | 9 | 0.78$^{a}$ | 0.07 |
| | | *TM 0m* | 20 | 1.14$^{b}$ | 0.14 | 20 | 1.19$^{a}$ | 0.20 | 19 | 1.26$^{b}$ | 0.31 |
| | | *TM 0.3m* | 20 | 1.13$^{b}$ | 0.10 | 10 | 1.30$^{a}$ | 0.22 | 18 | 1.31$^{b}$ | 0.09 |
| | Forest | *MM above* | 12 | 1.35$^{ab}$ | 0.24 | 12 | 1.38$^{c}$ | 0.16 | 13 | 1.32$^{c}$ | 0.12 |
| | | *MM below* | 12 | 1.41$^{bc}$ | 0.08 | 11 | 1.31$^{c}$ | 0.08 | 14 | 1.25$^{cd}$ | 0.10 |
| | | *MM 0m* | 10 | 1.25$^{ab}$ | 0.14 | 9 | 1.03$^{ab}$ | 0.20 | 10 | 1.16$^{cd}$ | 0.05 |
| | | *MM 2m* | 10 | 1.26$^{ab}$ | 0.10 | 8 | 1.15$^{ac}$ | 0.20 | 12 | 1.13$^{bd}$ | 0.15 |
| | | *Ref micro* | 51 | 1.40$^{b}$ | 0.28 | 58 | 1.31$^{c}$ | 0.14 | 49 | 1.15$^{d}$ | 0.13 |
| | | *Ref deep* | 5 | 1.42$^{ab}$ | 0.07 | 2 | 1.37$^{ac}$ | 0.01 | 5 | 1.33$^{cd}$ | 0.10 |
| | | *TM above* | 10 | 1.16$^{ab}$ | 0.26 | 11 | 1.00$^{a}$ | 0.23 | 9 | 0.92$^{a}$ | 0.12 |
| | | *TM below* | 10 | 1.04$^{a}$ | 0.18 | 12 | 0.99$^{a}$ | 0.15 | 9 | 0.95$^{ab}$ | 0.12 |
| | | *TM 0m* | 20 | 1.20$^{ac}$ | 0.19 | 25 | 1.22$^{bc}$ | 0.14 | 18 | 1.17$^{cd}$ | 0.14 |
| | | *TM 0.3m* | - | - | - | 26 | 1.26$^{c}$ | 0.11 | 19 | 1.15$^{d}$ | 0.15 |
| | Cashew | *MM above* | 23 | 1.48$^{c}$ | 0.18 | 11 | 1.41$^{a}$ | 0.17 | 18 | 1.35$^{d}$ | 0.16 |
| | | *MM below* | 13 | 1.42$^{c}$ | 0.14 | 11 | 1.30$^{ab}$ | 0.16 | 8 | 1.28$^{bd}$ | 0.10 |
| | | *MM 0m* | 8 | 1.33$^{bc}$ | 0.11 | 8 | 1.33$^{ab}$ | 0.11 | 10 | 1.33$^{cd}$ | 0.08 |
| | | *MM 2m* | 11 | 1.36$^{bc}$ | 0.10 | 16 | 1.25$^{ab}$ | 0.17 | 12 | 1.36$^{cd}$ | 0.09 |
| | | *Ref micro* | 52 | 1.44$^{c}$ | 0.09 | 49 | 1.23$^{ab}$ | 0.17 | 37 | 1.48$^{c}$ | 0.11 |
| | | *Ref deep* | 5 | 1.49$^{c}$ | 0.04 | 4 | 1.15$^{ab}$ | 0.07 | 3 | 1.42$^{cd}$ | 0.03 |
| | | *TM above* | 8 | 0.94$^{a}$ | 0.46 | 10 | 1.30$^{ab}$ | 0.18 | 10 | 1.00$^{a}$ | 0.15 |
| | | *TM below* | 8 | 1.08$^{ab}$ | 0.62 | 10 | 1.26$^{ab}$ | 0.22 | 10 | 1.09$^{ab}$ | 0.21 |
| | | *TM 0m* | 16 | 1.37$^{bc}$ | 0.16 | 19 | 1.18$^{b}$ | 0.13 | 20 | 1.37$^{cd}$ | 0.10 |
| | | *TM 0.3m* | 16 | 1.42$^{c}$ | 0.10 | 20 | 1.19$^{b}$ | 0.13 | 19 | 1.42$^{cd}$ | 0.13 |

The bulk density in and around termitaria is summarized for al fields in Figure 8.6. The bulk density at 0-5 cm in the reference pit is significantly higher than that at 40-45 cm, which is probably the result of compaction of the ground through trampling in agricultural fields and plantations. The outer wall of the MM is significantly denser than the reference soil at 40 cm. On top of the MM and between 0 and 1m depth bulk densities are also higher, but not significant. Close to the mound the upper soil has a lower bulk density, probably due to less trampling or higher organic matter contents. Bulk densities were significantly lower in most TM and sometimes in the environment of these mounds. This is the result of the many pores and holes in and around termite nests. Bulk densities for each field separately are calculated (Table 8.6) and will be used for the calculation of carbon densities (next paragraph).

## 8.5.4. Total influence of mounds on SOC stocks

In Table 8.7 the total influence of termite mounds on OC stocks in the 9 fields is discussed. Total carbon densities for the reference soils vary from 71 (Naliendele crops) to 371 (Nachingwea crops) Mg $ha^{-1}$. These are within the range of carbon densities for different soils and land uses discussed in Chapter 4.

The number of TM seems somewhat arbitrary, ranging from 5 to 152, although fewer mounds were observed in agricultural fields. The number of MM in most fields ranges between 2 and 6 per hectare. 21 MM were found in the Nachingwea cashew grove. These mounds are much smaller than in the other fields and probably belonging to another *Macrotermitinae* species, although this was not verified.

Large areas of the farmers' fields can be occupied by termite mounds. MM occupy, due to their large size, 90$m^2$ $ha^{-1}$ on average and in one case more than 200 $m^2ha^{-1}$. TM are mostly so small that even if there are more than 150 mounds present, they still cover only a few square meters (1.6 $m^2$ $ha^{-1}$ on average). Although the small TM had always significant higher OC levels than the reference soil, this effect is only multiplied by the small volume, therefore the C stock of small mounds only ranges between 1 and 76 kg C per hectare. MM have lower percentages of OC but this effect is observed in a large volume of soil. The C stock of the above ground part of MM ranges between 0.4 and 18.7 Mg C $ha^{-1}$.

Not only termite mounds have increased C densities but also the soil under and around the mounds. It was calculated that soil under MM and in a ring of 3.8m wide and 0.8 m depth around MM and soil under and around TM till 1.2m distance and 0.7m depth have increased OC concentrations. By adding these to the OC of the mounds, the total C density of the termite-influenced fields can be compared to the reference soil. In all cases this leads to an increase in total C stock, ranging from 2.2 to 37.8 Mg $ha^{-1}$. This is an increase of 2.4 to 21.5! Of course it still has to be kept in mind that this study does not give proof that the 'reference' is actually the same as the situation without termites.

***Table 8.7 Impact of MM and TM on total carbon densities of the 9 fields***

| Field | Reference soil | Termitinae Mounds | | | | Macrotermitinae Mounds | | | | Total | Increase | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | OC (0-1 m) | Number of Mounds | Area Mounds | Volume Mounds | OC Mounds | Number of Mounds | Area Mounds | Volume Mounds | OC Mounds | OC | Total OC – reference OC | |
| Land Use | (Mg $ha^{-1}$) | $ha^{-1}$ | ($m^2 ha^{-1}$) | ($m^3 ha^{-1}$) | (Mg $ha^{-1}$) | $ha^{-1}$ | ($m^2$ $ha^{-1}$) | ($m^3$ $ha^{-1}$) | (Mg $ha^{-1}$) | (Mg $ha^{-1}$) | (Mg $ha^{-1}$) | (%) |
| **Naliendele** | | | | | | | | | | | | |
| **Crop** | 71.206 | 18 | 1.17 | 0.66 | 0.014 | 3 | 43.24 | 35.75 | 0.561 | 73.43 | 2.224 | 3.123 |
| **Forest** | 90.053 | 35 | 0.32 | 0.1 | 0.003 | 2 | 68.30 | 75.34 | 1.535 | 94.42 | 4.367 | 4.849 |
| **Cashew** | 92.613 | 31 | 0.98 | 0.45 | 0.006 | 2 | 17.73 | 87.53 | 1.570 | 94.87 | 2.257 | 2.437 |
| **Nachingwea** | | | | | | | | | | | | |
| **Crop** | 371.366 | 5 | 0.08 | 0.03 | 0.001 | 5 | 121.79 | 73.40 | 2.857 | 381.38 | 10.014 | 2.697 |
| **Forest** | 235.346 | 27 | 0.63 | 0.19 | 0.006 | 3 | 127.25 | 113.38 | 4.241 | 255.71 | 20.364 | 8.653 |
| **Cashew** | 271.191 | 17 | 1.12 | 0.42 | 0.006 | 21 | 57.17 | 13.45 | 0.389 | 278.73 | 7.539 | 2.780 |
| **Nanyanga** | | | | | | | | | | | | |
| **Crop** | 133.129 | 46 | 2.64 | 1.1 | 0.065 | 2 | 50.82 | 26.74 | 0.641 | 137.89 | 4.761 | 3.576 |
| **Forest** | 258.912 | 53 | 1.10 | 0.55 | 0.018 | 6 | 106.50 | 92.78 | 3.373 | 275.38 | 16.468 | 6.360 |
| **Cashew** | 175.169 | 152 | 6.73 | 2.42 | 0.076 | 4 | 215.77 | 287.01 | 18.663 | 212.90 | 37.731 | 21.540 |
| **Average** | 188.776 | 43 | 1.64 | 0.66 | 0.021 | 5 | 89.84 | 89.49 | 3.759 | 200.523 | 11.747 | 6.223 |

# 8.6 Discussion and conclusions

Termite diversity decreased from natural forests to cashew plantations and agricultural fields, reflecting the change in canopy cover and resulting effects on soil humidity, as described by Eggleton et al. (1996). Soil feeding genera are most affected by conversion from forest to crops, which is confirmed by many authors. On the other hand cropping favours many genera known as pests. Six genera are known to build mounds. The number of TM is lower in agricultural fields since small mounds are easily removed by farmers. It is also possible that the drying out of mounds in agricultural land scares away the original populations, although the mound structure itself may persist for many more years. On average 5 MM are found in each field, which confirms previous research, where mound density of *Macrotermitinae* is estimated between 1 and 10 $ha^{-1}$ (Bouillon, 1970; Pomeroy, 1976, 1983). Five MM $ha^{-1}$ clearly reflects the foraging zone of 35 to 50m for *Macrotermitinae* species in dry tropical Africa, as described by Arshad (1982). The number of mounds is independent of land use because local people usually do not remove these large mounds when clearing land for agriculture or plantation establishment.

Organic carbon levels of MM and TM are comparable to those found in literature (Harris, 1949; Holt & Lepage, 2000). OC in the aboveground part of MM are on average 1.5 times higher than the reference micro-pits (0-40 cm). Higher amounts were sometimes observed within the nest structure and on top of the mounds, because of the increased litter input from plants. This generally small increase results from the use of saliva in building the mounds as described in literature. Mound carbon contents reflect the amount of SOC in the surrounding subsoil, which is the main building material for MM. Higher subsoil clay contents of Nitisols and Acrisols explain the higher average MM C contents in Nachingwea and Nanyanga.
OC levels of TM are on average 3.5 times higher than the reference micro-pits, which is the result of incorporation of faeces in the mound material. The increased organic matter is stabilised in the mound through adsorption to the clay fraction. Since soil-feeders mainly use materials from the surface 10 cm of the soil for the construction of mounds, and since the topsoil in Nanyanga has a sandy clay loam texture (see Table 7.1), the highest levels of OC are found in the TM of Nanyanga. Topsoil textures of Naliendele and Nachingwea are more sandy and OC levels in the mounds are therefore lower.
When original OM levels are high, as in the Nachingwea cropping field, no increase in mean OC is observed in the mound, which is confirmed by literature (Anderson & Wood, 1984).

Calculating carbon densities of mounds reveals that on average a MM (aboveground) contains 751.8 kg C, while only 0.5 kg C is stored in an average TM. Over 1 ha these add up to 21kg OC stored in TM and 3759 kg OC in MM. Thus, although TM raise OC levels much more, due to their small volumes their effect on field level carbon stocks is much smaller. OC is not only enriched in the mound structures but also under and around mounds. By approximating the sphere of influence around a mound by a cylinder segment 3.8m wide and 0.8 m deep around MM and 1.2m wide and 0.7m deep around TM, carbon stocks for the whole field (to 1m depth) were calculated and compared to the reference carbon stocks. It can be concluded that on average the presence of termite mounds and termite-modified soil increases the C density with 12 Mg $ha^{-1}$ or 6%! In Arenosols and Ferralsols this could be of the magnitude of major land use changes, such as conversion from forest to cashew groves. Thus by overlooking the local hotspots created by termite mounds, SOC stocks can

be strongly underestimated, and by imprecise sampling of these local heterogeneities, land use change induced increases or decreases of SOC could be obscured.

An adequate and precise sampling strategy is therefore necessary in fields with large numbers of termite mounds. However, when looking at the actual coverage of mounds in the field, this is on average only 91$m^2$ $ha^{-1}$, or less than 1%. This means that in random or regular sampling, on average only 1 out of 100 samples would be located on a mound. The influenced soil around termitaria covers about 10% of the field surface. If samples are taken randomly from these different pools in the field, coefficients of variation will become very high and the possibility exists that certain pools are not sampled adequately, even if they have a significant impact on the carbon pool of the total field. With such high coefficients of variation, it will become even more difficult to discern differences between land uses or soil types. However by taking into account termite induced heterogeneity and by sampling the different landscape components separately (Figure 8.7), coefficients of variation can be reduced. By using the average ground cover distribution across the landscape, a weighted estimate of SOC can be made. This technique is comparable to a study made by Reeder (2002) who found local concentrations of SOC beneath grasses and shrubs compared to bare ground in a rangeland and who also suggests stratified sampling in the different landscape components.

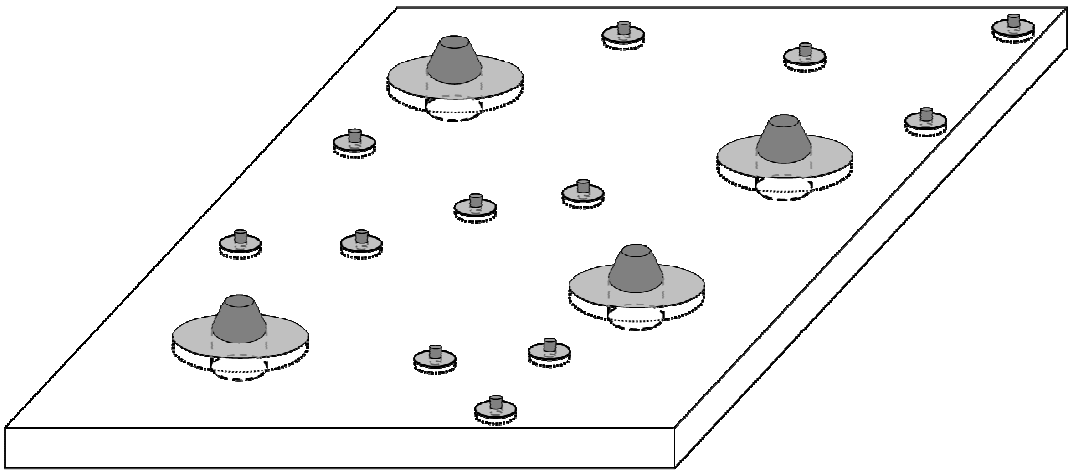


***Figure 8.7 Different zones within a field for stratified sampling: MM and TM, soil under MM, zones of influence around mounds with a certain radius and depth and reference soil.***

It is possible to further stratify sampling on a small scale, when paying attention the heterogeneity within MM (difference between outer wall, nest structure and top of the mound), although differences between these parts were not significant. Since breaking down and sampling termite mounds is very labour-intensive and environment-unfriendly, it would be opportune to limit the number of sampled termitaria. From the results it was concluded that carbon densities of mounds were highly dependent on the parent material and soil type, but not so much on land use. Therefore in future research it is advised to sample mounds on every soil type, but it is not necessary to sample mounds in fields with different land uses.

It can be concluded that both MM and TM influence soil carbon stocks of fields in all land uses and soil types. Stratified sampling in and around these mounds is absolutely necessary to correctly estimate SOC stocks of these fields, and to be able to distinguish management or land use induced changes in SOC.

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# 9 General conclusions

The main research question of this thesis was: How large is the SOC stock under different soils and land uses of southeastern Tanzania? To be able to answer this question, several steps had to be taken.

First, the type and extent of different soil types in the study area had to be assessed, by making an updated soil map. Parent material and topography mainly determined the soil type, which results in a high variety of soil types throughout the area. The oldest ones of the region are those of the big plains situated on Basement rocks. They are deep and homogeneous with clayey subsoil: mainly Arenic or Ferralic Phaeozems on coarse-grained gneisses, deep red Eutric Nitisols in the low areas of the central plains and Lixisols or Luvic Arenosols on the more inclined terrain. All soils derived of the strongly weathered sandstone beds of Lower Cretaceous origin are deep and sandy: Arenic Ferralsols, Arenosols and (Ferralic) Arenic Phaeozems are the most common soils on the high plateaus while Arenic Alisols and Acrisols were observed on the slopes. On marine deposits of grey clays, marls and limestones mainly Gleysols and Vertisols are formed. The most common soils on quaternary deposits along rivers are Vertisols, Gleysols, Fluvisols and Phaeozems. It can be concluded that the available commonly used soil map is not useful as a base for a soil carbon study due to many errors. These errors are the result of a classification system that has developed since then, a difference in scale and a research objective that focussed mainly on agricultural areas. The new soil map is more detailed, uses a recent classification system and recognises certain soil types (e.g. Nitisols) which were not observed in the old maps but which can be very important in a SOC study. Therefore it is strongly recommended to use the new map for future studies. It can further be recommended to extend the soil map to the whole area of Southeast Tanzania (including the northern part of Lindi Region and the district of Tunduru in the Ruvuma region).

The second step was to determine the type and extend of land use and land use change in the study area. The original vegetation of coastal forest, miombo woodland and mangrove forest has been replaced largely by secondary vegetation and agriculture. The coastal forest has suffered most of human intervention. The reason is the greater population in these areas, which is a historical development. Secondary shrubland covered most of the coastal area in 1997, with crops and tree crops growing mainly in the river valleys. Towards 2005, the area of cropland extended considerably, while tree crops were grown on the more infertile sandy soils. On the densely populated Makonde plateau forest was cleared mainly for cashew, except on the higher elevations, and later also cropland. The Rondo plateau has always been less populated and some of the original forest area could be preserved, but tree crops have been introduced largely. The area that was originally covered with miombo woodland was less disturbed and a large area still remains. However, the southern plains and the central area of Nitisols were extensively planted with crops and tree crops.
Compared to national data of land use and land use change, the wide extend of cashew groves is remarkable. This is logical since southeastern Tanzania is the main producer of cashew in the country.

Attributing SOC stocks to the soils and land uses that were just described can be done after calculating the SOC density of 210 profiles from the reference dataset and 354 profiles sampled by the author. To derive SOC from SOM (measured with loss-on-ignition), two regression equations were developed which are valid for the study area:
A-horizon: SOC = -0.248 + 0.411 SOM
B-horizon: SOC = -0.202 + 0.240 SOM

where SOC stands for soil organic carbon (in %) and SOM for soil organic matter (in %).
The intercept and the low value of the slope parameter for the subsoil can be explained by weight loss of other, inorganic, soil constituents. In the soils of the study area, this additional weight loss could be attributed to the desorption of clay water from kaolinite, removal of hygroscopic water of vermiculite and illite, dehydration of gibbsite and goethite and dehydroxylation of gibbsite, goethite and hydroxyl-interlayered minerals. All these minerals are very common in the old soils found in the area. In future studies it is advised to preheat all for 2 hours at 200°C to reduce the errors made by loss on ignition and to reduce the intercepts. It is also recommended to develop regression equations including texture variables.
To estimate bulk densities for profile descriptions lacking this feature, a pedotransfer function was generated:
$BD = 1.575 - 0.262 \log_{10}(clay) + 0.039 \log_{10}(depth)$
where BD stands for bulk density ($g.cm^{-3}$), clay for the 0-2 µm fraction (%) and depth for sampling depth (in cm). The bulk density depends in the first place on the clay content, which can be attributed to the development of microstructures caused by the aggregation of negatively charged clay minerals with sesquioxides. The fact that the functions do not depend on OC content, which distinguishes them from most relationships found in literature, emphasises the importance of making regional pedotransfer functions instead of relying on existing ones.
The vertical evolution of SOC was estimated and used in profiles where SOC was only measured to a certain depth:
In grassland and cropland: $\Delta \text{ Ln SOC} = -48.7 \Delta \text{ depth}$
in cashew groves (eventually intercropped): $\Delta \text{ Ln SOC} = -81.5 \Delta \text{ depth}$
and in woodlands and shrublands: $\Delta \text{ Ln SOC} = -93.4 \Delta \text{ depth}$
where SOC is soil organic carbon (%), depth is sampling depth (cm) and Δ SOC is the SOC difference between two depths (Δ depth). In woodlands and bushlands a high proportion of SOC is stored in the upper layers and SOC distribution is shallow, as a result of the quality of C inputs. The deeper distribution of C in croplands could also be the result of soil disturbance during clearing and establishing of the field, although soil preparation and ploughing is limited in the study area. The vegetation structure of cashew groves shows elements of the two other systems with a tree layer of cashew trees and sometimes an undergrowth of grass or crops.

With the previously described methodologies it is now possible to calculate SOC stocks for all land use-soil units and to answer the first question. The soils that can store the highest amounts of SOC in the study area are Vertisols, Phaeozems, Umbrisols and Nitisols (average SOC stock of 106 $Mg.ha^{-1}$). Although they cover less than 40% of the total area, they contribute to almost 60% of the total SOC stock in 2005. However, they also contributed to 50% of the total SOC loss due to land use changes between 1997 and 2005. This can be mainly attributed to the loamy Phaeozems and Umbrisols, which have a high SOC content in their A-horizon but which offer no protection in organo-mineral complexes such as in clayey soils. After land use change, SOC is easily lost from these soils. Alisols, Acrisols, Lixisols, Ferralsols, Arenosols and Ferralic/Arenic Phaeozems have significantly lower SOC stocks (average of 87 $Mg.ha^{-1}$). SOC stocks of Gleysols are intermediate at 87 $Mg.ha^{-1}$, which is mainly the result of the impeded growth of bushlands on these soils. Remnants of closed forest, woodlands and bushlands of more than 20 years have SOC stocks between 66 and 70 $Mg.ha^{-1}$. Although this is low for forests in general, figures are

comparable to SOC stocks under woodland found in literature. The low SOC stocks can be attributed to the retaining of natural vegetation on the poorest soils, to the open structure of the vegetation with often little groundcover and to the disturbances by humans and fire. However, if woodlands are preserved on fertile soils they can have high SOC stocks, for example 120 $Mg.ha^{-1}$ on Nitisols. The traditional cropping system, which consists of several years of cultivation followed by several years of bush fallow, is able to maintain high SOC stocks. The young bushland vegetation, with a complex mixture of grasses, shrubs and young trees, has an average SOC stock of 120 $Mg.ha^{-1}$. After clearing, fields are established on the fertile grounds and have an average SOC stock of 98 $Mg.ha^{-1}$ (cropped fields without cassava). However, more than half of these cropped fields (without cassava) are found on the most fertile soil types described above. On less fertile soils and when cropping becomes continuous, cassava becomes most important, since it is the most resistant crop. SOC stocks under cassava are more than halved (39 $Mg.ha^{-1}$) than under other crops. Shortening of the fallow period has been observed for a long time. If the fallow system is abandoned completely and converted to permanent agriculture with cassava or other crops, this will have serious implications on the SOC stocks. Another threat for the regional SOC stocks is the expansion of cashew plantations, which in 2005 already cover 33% of the study area. After cassava, cashew groves have the lowest average SOC stock (50 $Mg.ha^{-1}$) which is the result of the removal of grass, undergrowth and litter by farmers to facilitate harvesting of cashew seeds. Planting other crops between the young trees (<20 yr) enhances the mean SOC stocks (to 79 $Mg.ha^{-1}$) but after 20 years this effect completely disappears, since crops can only be grown in the small spaces that remain between the old trees. Grasslands, rice fields and homestead gardens are less common land uses, which occur mostly on the fertile soils and which have among the highest SOC stocks (mean total values between 114 and 128 $Mg.ha^{-1}$). Total SOC stocks of the study area were estimated at 34.50 Tg in 1997. This reduced with 14% due to land use changes in 8 years time (to 2005). It can be concluded that intensification of the agricultural system by reducing the fallow period and planting mainly cassava on the depleted soils as well as the large expansion of the cashew monocultures have causes a serious loss of SOC from the study area. Restoration of the traditional fallow system, intercropping of cashew trees with crops on a substantial area of the field, also after 20 years, and reforestation could be used to restore SOC stocks. However, this study was conducted based on land uses spread in space. It is difficult to discern between the mutual effect of land use and soil: do certain land uses deplete SOC or are they grown preferentially on depleted soils? Therefore in future research space should be replaced by time: how do land use changes influence SOC stocks in the same plot, after a certain period of time.

The second important question of this thesis was: how can SOC measurements be optimized for this region? First a spatial variability study was conducted in 5 common forest/woodland/plantation types of the study area. Cost-effective sampling strategies for estimating SOC depend highly on the forest type, the scope of the research project and the measuring method. Volumetric sampling is strongly advised since it leads to a more cost efficient sampling strategy than measuring mass percentages. In the 5 forest types of this study, variogram ranges and thus sampling distances tend to be very variable. These differences were the result of mainly soil natural intrinsic variation, topography and cultivation practices. The impact of vegetation structure only can cause a variation in ranges between tens and hundreds of meters. As a result, not only sample sizes but also sample intervals will be entirely different for various forest types. The optimal sampling distance for measuring mean SOC stocks varies between 36 m (in the patchy miombo woodland) and 422 m (in the homogenized cashew plantation); while in the pine plantation, which has no

spatial structure, samples can be arranged randomly. Sample sizes fluctuate between 24 and 289 (0.5 Mg $ha^{-1}$ precision) and between 1 and 18 (2 Mg $ha^{-1}$ precision) for respectively cashew plantation and coastal forest. A rectangular grid with a sample interval of 25m can be used for SOC mapping with a point kriging estimation error of 3.0 Mg $ha^{-1}$ in the coastal forest, 2.6 Mg $ha^{-1}$ in miombo woodland, 2.2 Mg $ha^{-1}$ in the teak plantation and 1.1 Mg $ha^{-1}$ in the cashew plantation. At longer sample intervals the kriging estimation error increases quickly for the miombo woodland and more slowly for the forests with longer ranges. Block kriging strongly lowers the error. The pine plantation has no spatial structure and its best soil map has an average C content attributed over the whole field. When sampling new types of forests it is possible to refine the sampling strategy based on a new spatial variability study. This can be based on a regular grid with sampling distances of half the range identified in this study. It has been proven that it is important to define the research objectives, sampling precision and the specific forest types before the start of the study and to adapt the sampling design. Using the same sampling strategy for all cases will result in oversampling and economic loss in homogeneous plantations such as cashew, and in unacceptable high error in coastal and miombo forests with a high variability. The sampling strategy for estimating the mean C stock is different from the strategy for soil C mapping based on points or blocks. If no spatial correlation can be seen, as in the pine forest, the mean value can be attributed to the whole field, therefore further sampling for soil mapping is a waste. For future research it is strongly advised to conduct similar studies on other land uses and soil types of the study area, in order to optimize sampling strategies. The spatial variation at other soil depths than the upper horizon should be examined in order to get a better idea of the optimal sampling strategy for measuring SOC stocks in the whole soil profile.

Besides spatial structures in SOC resulting from vegetation-induced patterns, other factors could locally alter SOC spatial heterogeneity. One such factor in the Tanzanian landscape is the presence of termites and their mounds, which can have very high densities. Therefore a characterization of the spatial patterns of SOC in and around termite mounds in a plot was made in order to adapt sampling strategies to these heterogeneities in the soil. Organic carbon levels of mounds are comparable to those found in literature. OC in the Macrotermitinae mounds (large mounds) are on average 1.5 times higher than the reference micro-pits (0-40 cm). This generally small increase results from the use of saliva in building the mounds as described in literature. Mound carbon contents reflect the amount of SOC in the surrounding subsoil, which is the main building material for Macrotermitinae. OC levels of Termitinae mounds (small mounds) are on average 3.5 times higher than the reference micro-pits, which is the result of incorporation of faeces in the mound material. The increased organic matter is stabilised in the mound through adsorption to the clay fraction. Calculating carbon densities of mounds reveals that on average a Macrotermitinae mound (aboveground) contains 751.8 kg C, while only 0.5 kg C is stored in an average Termitinae mound. Over 1 ha these add up to 21kg OC stored in Termitinae mounds and 3759 kg OC in Macrotermitinae mounds. Thus, although Termitinae raise OC levels much more, due to the small volume of their mounds the effect on field level carbon stocks is much smaller. OC is not only enriched in the mound structures but also under and around mounds. On average the presence of termite mounds and termite-modified soil increases the C density with 12 Mg $ha^{-1}$ or 6%. In Arenosols and Ferralsols this could be of the magnitude of major land use changes, such as conversion from forest to cashew groves. Thus by overlooking the local hotspots created by termite mounds, SOC stocks can be strongly underestimated, and by imprecise sampling of these local heterogeneities, land use change induced increases or decreases of SOC could be obscured. However by taking into account termite induced heterogeneity and by sampling the different

landscape components separately, coefficients of variation can be reduced. By using the average ground cover distribution across the landscape, a weighted estimate of SOC can be made. Stratified sampling in and around these mounds is necessary to correctly estimate SOC stocks of these fields, and to be able to distinguish management or land use induced changes in SOC.

In this study SOC stocks were calculated to a fixed depth of 1m, for comparison with international data. This method may however overestimate SOC in high bulk density soils, especially when treatments affect bulk density. In the future it could be recommended to recalculate the quantity of SOC on an equivalent mass basis. Since in the deep soils of the study areas large amounts of SOC are stored in the deeper layers, it would be advised to examine the SOC below 1m depth. This research should certainly be extended with information on SOC in the litter layer, since this part of the soil can store very different amounts of SOC depending on the land use and it is of great importance in carbon budgeting. Whereas this study mainly focussed on changes in SOC upon land use change because of differences in carbon inputs and mineralisation rates, the effect of erosion on SOC after land use change provides many opportunities for further research.

This thesis proves that regional estimates of SOC stocks are necessary to refine global estimates, because they are dependent of many site-specific factors. This work can be used as a guideline for estimating SOC stocks in other regions, based on locally adapted monitoring and measuring tools. With adapted strategies for sampling in the field as well as measuring in the laboratory and extrapolating to total C stocks, it is possible to obtain high levels of accuracy without economic loss.

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# Software

Unless otherwise stated, following software has been used in this thesis:

### Statistics:

SPSS: version 12.0, SPSS Inc., 2003, Chicago IL, USA.

### All maps and GIS-interpretation

Arcview: Arcview 3.2 by ERSI., 1992-2000, Environmental systems research institute.
ArcGis: Arcgis 9.1 by ESRI, 2005 Environmental systems research institute.

### Geostatistics

Variowin 2.2: by Pannatier, Y., 1996. VARIOWIN: Software for Spatial Data Analysis in 2D. Springer Verlag, New York, USA.

OSSFIM developed by McBratney, A.B. & Webster, R., 1981. (The design of optimal sampling schemes for local estimation and mapping of regionalized variables, (II) Program and examples. Computers and Geosciences, 7: 335-365.) and implemented in Gstat by Pebesma, E.J. & Wesseling, C.G., 1998. (Gstat: a program for geostatistical modelling, prediction and simulation. Computers & Geosciences, 24 (1): 17-31).