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Effects of red brick production on land use, household income, and greenhouse gas emissions in Khartoum, Sudan

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Abstract

In Khartoum (Sudan) a particular factor shaping urban land use is the rapid expansion of red brick making (BM) for the construction of houses which occurs on the most fertile agricultural *Gerif* soils along the Nile banks. The objectives of this study were to assess the profitability of BM, to explore the income distribution among farmers and kiln owners, to measure the dry matter (DM), nitrogen (N), phosphorus (P), potassium (K) and organic carbon (C_{org}) in cow dung used for BM, and to estimate the greenhouse gas (GHG) emissions from burned biomass fuel (cow dung and fuel wood). About 49 kiln owners were interviewed in 2009 using a semi-structured questionnaire that allowed to record socio-economic and variable cost data for budget calculations, and determination of Gini coefficients. Samples of cow dung were collected directly from the kilns and analyzed for their nutrients concentrations. To estimate GHG emissions a modified approach of the Intergovernmental Panel on Climate Change (IPCC) was used. The land rental value from red brick kilns was estimated at 5-fold the rental value from agriculture and the land rent to total cost ratio was 29 % for urban farms compared to 6 % for BM. The Gini coefficients indicated that income distribution among kiln owners was more equal than among urban farmers. Using IPCC default values the 475, 381, and 36 t DM of loose dung, compacted dung, and fuel wood used for BM emit annually 688, 548, and 60 t of GHGs, respectively.

Keywords: Brick kilns, biomass fuel, Gini coefficient, GHG emissions, return to land

1 Introduction

Population growth and urbanization enhance the needs of urban residents for food, energy, and shelter. These enhance the pressure on land which is reflected in strong increases of agricultural land prices in urban areas (Bryld, 2003; Sazak, 2004; Muto, 2006; Prain, 2006; Lankoski & Ollikainen, 2008; Lovell, 2010). Rising prices for agricultural land often lead to the transfer of agricultural land use from inner city areas to more peripheral locations (Singh & Sarfaraz Asgher, 2005; Simatele & Binns, 2008).

A recent remote sensing study provided solid evidence of the large spatial expansion of Khartoum, the capital city of Sudan, over the past 50 years (Schumacher *et al.*, 2009). During this expansion process the ratio of built-up area to urban agricultural area has increased from 2.0 in 1972 to 4.7 in 2009. From 1958 to 2009 this has led to a decrease of agricultural area in the core zone of the city by 60 % (Schumacher *et al.*, 2009). Accordingly, demand for construction materials such as bricks has increased as their production provides an employment opportunity for the urban poor (Aubry *et al.*, 2010). In Khartoum brick making (BM) is mainly prac-

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ticed on the Blue and River Niles banks, the most fertile lands locally referred to as *Gerif*, where it competes with urban agricultural activities that are traditionally practiced there (El-Karouri, 1979; Jensen & Peppard Jr, 2004; Aubry *et al.*, 2010). To integrate BM into the diverse land use pattern of urban areas remains a challenge to the city municipality and to urban planners (Lovell, 2010).

Red bricks are the major building material in Sudan's urban areas (MEPD & HCENR, 2003) and are largely produced using traditional biomass energy such as from cow dung and fire wood. Less than 2 % of total red bricks is produced using fossil fuel (Alam & Starr, 2009). Red brick making is known as an important source of urban greenhouse gas (GHG) emissions given the low combustion efficiency of the fuels used (Streets & Waldhoff, 1999). The main components in the BM process are loose and compacted cow dung, clay, water, and fuel wood (Alam & Starr, 2009) wherein clay slurry made from Nile flood sediments is mixed with loose cow dung, pressed into moulds, and left to dry in the sun. Subsequently, the raw bricks are burned using compacted cow dung and wood as a source of energy (Alam, 2006).

During the last decades the overall production of red bricks in Sudan has strongly increased from an estimated 134 Million in 1975 to 1,804 Million in 2004 and to 2,800 million in 2006 (Hamid, 2002; Alam, 2006). In Sudan the total kiln number increased from 1,750 in 1995 to 3,450 in 2005, of which 2000 are located in Khartoum (Alam & Starr, 2009). Typically BM is a small-scale, labour intensive industry (Jensen & Peppard Jr, 2004) and countrywide the number of workers employed in this sector amounts to about 35,000 of which 50 % are in Khartoum and 38 % in the Central States (Alam, 2006). Most of the labourers are working on a temporary basis because their payment is based on the quantity produced and not on working hours (Jensen & Peppard Jr, 2004). The health risks related to this activity, particularly exposure to dust, combustion gases, and to heat, makes it difficult to work continuously in a kiln (Alam, 2006). Also, the annual floods of the River Nile, force most of the kilns to stop operation from July to September.

Practicing of BM on the River Nile banks in the midst of agricultural lands has multiple effects on vegetable and fruit tree production (Alam, 2006). Due to the heat, soot, and smoke particles deposited on the leaves, plant respiration and photosynthesis may be affected (Alam, 2006). This has also been reported from Vietnam where kilns are located near rice fields (Jensen & Peppard Jr, 2004; Le & Oanh, 2010). Additionally, the soil pit excavation for BM on the River banks make agricultural areas more vulnerable to the erosive floods of the River Nile (Ahmed *et al.*, 2010) and it may prevent cultivated land to be enriched by sediment deposits (Alam, 2006). Also, the soil surface will be transformed irreversibly (Singh & Sarfaraz Asgher, 2005). Last, the use of substantial amounts of fuel wood accelerates deforestation (MEPD & HCENR, 2003) and leads to the emission of GHGs such as carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), nitric oxide (NO), and nitrogen oxide (NO_X; Alam & Starr, 2009).

Following von Thünen's theory of a land rent gradient (von Thünen, 1930) the competing use for urban land should lead to a move of agricultural lands from inner city areas to the peri-urban space. This model, however, never been verified in Sudan, has been used elsewhere to study the effect of different factors on spatial shifts in land usages, value, and price (Sazak, 2004; Muto, 2006; Lankoski & Ollikainen, 2008).

Valuation of land usage maximizes income for land owners at the expense of land users for whom land is an input factor rather than a resource (Sazak, 2004). In a recent study Xu (2003) used the Lorenz curve and Gini coefficient as indicators of income equality among households, an approach which was also chosen in this study.

The overall objectives of this study were to examine the socio-economic characteristics of red brick kiln owners, to examine the benefit cost ratios (B/C) for agricultural activities and red brick production, to determine the dry matter (DM), nitrogen (N), phosphorus (P), potassium (K), and organic carbon (C_{org}) consumption in cow dung-based BM, to identify the reasons why cow dung is used for BM rather than as an organic fertilizer in urban vegetable production, to determine the cash value of cow dung and mineral fertilizers, and to investigate the contribution of brick kilns to GHG emissions.

2 Materials and Methods

2.1 Site description

The study area comprised the banks of the River Nile and the Blue Nile starting from the confluence of the Blue and White Nile in central Khartoum (15° 40´ N, 32° 30´ E, 382 m. a.s.l), located within the semi-desert climate zone of Sudan (Hamad & El-Battahani, 2005; Mubarak *et al.*, 2010). There are three climatic seasons (Elagib & Mansell, 2000), the hot dry summer (April to June), the autumn (July to September), and the cool dry winter (October to March), with mean monthly temperatures ranging from 22.1 to 33.7 °C. Average annual rainfall ranges from 100–300 mm (Hamad & El-Battahani, 2005; Mubarak *et al.*, 2010). High waters of the Nile typically coincide with heavy rainfalls from July to August leading to the occurrence of floods (Barakat, 1995; Hamad & El-Battahani, 2005). During these events the width of the River Nile increases from an average of 400 m to up to 1000 m (Davies & Walsh, 1997; Ahmed *et al.*, 2010). Flooding of the river banks for almost three months heavily influences the land use system in the affected areas (Thompson *et al.*, 2010).

2.2 Data collection

For this study a total of 49 red brick kilns were randomly selected and kiln owners or their agents were interviewed using a semi-structured questionnaire from July–August 2009. Kiln locations (Figure 1) were recorded using a hand-held Geographical Positioning System (GPS; Trimble Pathfinder, Sunnyvale, CA, USA). The data collected from the respondents included general information such as age, education, land ownership, number of kilns managed or owned, and length of time during which the kilns are operated (months per year). Detailed information about the inputs used in BM and prices of inputs and product were recorded for the different seasons.

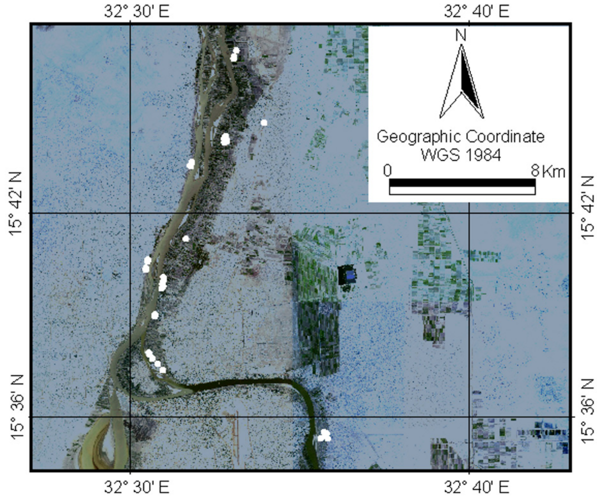

Fig. 1: *Google Earth Pro image (Google, Mountain View, CA, USA) of Khartoum, Sudan, 2009. The white dotes indicate the location of the 49 traditional kilns surveyed on the banks of the Blue Nile and the River Nile.*

On the other hand 15 intra-urban farmers and 31 peri-urban animal raisers were interviewed from July–August 2009 and information related to their land's share rental value and annual income for intra-urban farmers and annual returns from dung for the animal raisers was collected.

2.3 Data analysis

Descriptive analysis was used to identify the socio-economic aspects related to the kiln owners. The change ratio [100 * (Price at the end of season – Price at the beginning of season) / Price at the beginning of season] was calculated for all inputs and outputs. The cost value of inputs (mainly for land rent, loose dung, compacted dung, fuel wood, and labour), and other costs such as taxes and fees was calculated. Subsequently, the cost of production per 1000 bricks, the profitability of the activity (Total return – Total cost), and the Benefit cost ratio [(B/C) = (Total revenue / Total cost)] was computed. The Average Product (AP), which indicates the average productivity of each unit of variable input being used (Casavant *et al.*, 1999), for inputs and the average cost of inputs as loose dung, labour, biomass fuel, and other costs were also calculated.

To determine the financial impact of red brick and agricultural production for both intra-urban farmers and kilns owners, the Gini coefficient (G), a measure of income inequality, was used. The Gini coefficient ranges between 0 and 1, whereby 0 indicates perfect equality (everyone has the same income) and 1 corresponds to perfect inequality (one person has all available income, and everyone else has no income). This coefficient is derived from the Lorenz curve which describes the relationship between the cumulative percentage of the population and the income (Shideed & El Mourid, 2005). For the sake of this study the more practical Brown formula of the Gini coefficient was applied (Brown, 1994; Xu, 2003) whereby the net cash return (total cash receipt minus total cash payment) was used as data input:

$$G = \left| 1 - \sum_{k=0}^{n-1} (X_{k+1} - X_k)(Y_{k+1} + Y_k) \right|$$

Where:
G = Gini coefficient
X_k = cumulated proportion of the population variable, for $k = 0, \ldots, n$, with $X_0 = 0$, $X_n = 1$
Y_k = cumulated proportion of the income variable, for $k = 0, \ldots, n$, with $Y_0 = 0$, $Y_n = 1$
k = case number
n = number of cases

The Benefit cost ratio was calculated as: total revenue / total cost (Phillips & Phillips, 2005) to obtain the return per monetary unit spent on each activity.

2.4 Nutrient losses from cow dung and GHG emissions

To estimate losses of N, P, K and C_{org} in DM basis and GHG emissions (CO_2, CO, CH_4, N_2O, NO, and NO_X) from cow dung, loose and compacted dung samples were collected from different kilns and analyzed for their N, P, K, and C_{org} concentrations using standard labouratory procedures. In order to estimate the quantity of dung used annually and to produce 1000 bricks, loose and compacted dung density were measured (weight per volume). As respondents were questioned about the number of lorries used for brick production, the capacity of one lorry (DM weight contained in one dung-filled lorry) was estimated and used to calculate the consumption of N, P, K, and C_{org} in BM.

Prior to analysis loose and compacted cow dung samples were dried to constant weight at 65 °C and total N and C_{org} measured using a Vario MAX CN/CHN/CNS analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). To estimate P and K concentrations samples were oven dried at 105 °C for DM determination, burned at 550 °C, and the resulting ash dissolved in HCl. The P concentration was measured colorimetrically (Hitachi U-2000 spectrophotometer, Hitachi Ltd., Tokyo, Japan) according to the vanado-molybdate method (Gericke & Kurmies, 1952) and K was determined by flame photometry (Auto Cal 743, Diamond Diagnostics, Holliston, MA, USA).

Nitrogen and C gaseous losses from loose and compacted dung and from fuel wood were estimated using modified procedures from the Intergovernmental Panel on Climate Change (IPCC, 1996) as follows:

$$TC_r = TB_b \times FB_{ox} \times B_c$$

Where TC_r = total carbon released (t C), TB_b = total biomass burnt (t DM), FB_{ox} = fraction of biomass oxidized, and B_c = biomass carbon content (t C t DM^{-1}). A default value of 0.9 was used for the fraction of biomass oxidized for both types of biomass material (dung and wood). Under the assumption of complete combustion, a C concentration of 45 % was used for dung biomass C that is 0.45 t C t DM^{-1} (Alam & Starr, 2009).

Non-(CO_2) gaseous emissions (CO, CH_4, N_2O, NO, and NO_X) were calculated from the TC_r as follows:

$$\begin{aligned}
CO &= TC_r \times ER \times 28/12\\
CH_4 &= TC_r \times ER \times 16/12\\
N_2O &= TC_r \times ER \times N/C \times 44/28\\
NO &= TC_r \times ER \times N/C \times 30/14\\
NO_X &= TC_r \times ER \times N/C \times 46/14
\end{aligned}$$

Where the specific emission ratios (ER) for the Non-CO_2 gaseous were CO = 0.060, CH_4 = 0.012, N_2O = 0.007, NO = 0.121 and NO_X = 0.121 and N/C ratio in biomass = 0.01. Following the approach of Alam & Starr (2009), CO_2 emission was derived from CO-C, CH_4-C gaseous emission and TC_r as:

$$CO_2 = TC_r - (CH_4\text{-}C + CO\text{-}C) \times (44/12)$$

Emissions were calculated separately for loose and compacted dung; once using the IPCC default values for FB_{ox}, B_c and N/C ratio and once using our own data obtained from the labouratory analysis for the FB_{ox} ((Oven dry weight - Ash weight) / Oven dry weight)), B_c (t C t DM^{-1}) and the N/C ratio for loose and compacted dung. Emissions from the fuel wood burning were similarly calculated using only the IPCC default values (FB_{ox} = 0.9; B_c = 0.5 t C t DM^{-1}).

To estimate the removal from biomass wood used as fuel, a default density value of 0.65 t DM m^{-3} (Dixon *et al.*, 1991) was used to convert wood biomass of commercial round wood (t DM) into cubic meter (m^3); for branches and small trees (non-commercial wood) an expansion ratio of 1.90 was added (Brown *et al.*, 1989; Alam & Starr, 2009):
Total deforested wood (m^3) = Round wood (m^3) * 1.90.

3 Results

In 2009 about 76 % of the urban agricultural land was under share cropping whereby the land rent ranged from 25–33 % of cropping returns after deducting the variable costs such as seeds, fertilizer, and pesticides. Animal raisers preferred selling their dung to red brick producers rather than to farmers, on fixed periods, weekly or monthly, depending on herd size. The annual average return from manure was about 4,528.2 SDG (one Sudanese Pound = 0.4 US$) for average herd size of about 27.4 Tropical Livestock Unit (TLU; ILCA, 1990).

3.1 Socio-economic characteristics

Red brick kiln owners were on average 45 years old having from 2 to 15 family members, 77 % were educated (at least primary schooling), the majority had no other income than BM, and more than a tenth of the respondents had more than one kiln. Most of them depended on rented land, whereas farmers preferred share cropping because of the high rent value. Red brick production in the traditional kilns lasts 6–12 months annually with an average of 10 months. Only 16 % of the respondents were land owners, while most of them were renting their land (Table 1). The average rent value paid by kiln owners by far exceeded the average value received from farmers as return from agricultural land use.

3.2 Production inputs, cost and benefits

Clay, cow dung, wood, and labour are the main inputs used in the BM process. Input and output prices changed across seasons whereby the rainy season, from late July to end September, is called “off-season” and the dry season, from October to July, is the “production-season”.

Table 1: *Socio-economic characteristics of the interviewed brick kilns owners (n = 49) in Khartoum, Sudan, 2009. Data show means followed by their standard deviation.*

Parameter	*Mean* / %
Age (years)	44.7 (9.3)
Family size (members)	7.3 (2.4)
No of working months	9.8 (1.2)
Education (%)	77
Main activity (%)	
Brick making	86
Other	14
Land ownership (%)	
Own land	16.0
Rented land	79.5
Both (own & rented)	4.5
Kiln Number (%)	
One brick kiln	86
More than one kiln	14

Table 2: *Prices (in SDG* per t dry matter (DM)) of loose dung, compacted dung and wood among sampled from kiln owners (n = 49) in Khartoum, Sudan, 2009. Data show means followed by their standard deviation.*

Parameter	*% of kiln*	*Mean*	*Change ratio (%)*†
Loose dung			
Beginning of season	96	42.6 (5.7)	
Middle of season	92	55.1 (7.3)	
End of season	100	70.3 (7.2)	65.0
Average prices	100	55.1 (4.6)	
Compacted dung			
Beginning of season	85	15.8 (2.6)	
Middle of season	92	23.7 (4.1)	
End of season	92	25.5 (5.9)	61.4
Average prices	100	22.1 (4.1)	
Wood	100	343.8 (21.3)	
Red brick			
Beginning of season	100	93.7 (6.4)	
Middle of season	100	84.0 (4.8)	
End of season	100	75.2 (9.8)	–25.0
Average		84.1 (4.5)	

* SDG (New Sudanese Pound) ≈ 0.4 US$
† Change ratio (%) = (((price at the end of season – price at the beginning of season) / price at the beginning of season) * 100)

The loose dung average price ranged from 43–66 SDG per t DM with an average of 55 SDG per t DM while the compacted dung average price ranged from 12–29 SDG per t DM with an average of 22 SDG per t DM (Table 2). Most of the interviewed kiln owners indicated that during the off-season, the price of loose dung was lowest and started to increase only at the beginning of the production season, due to the higher competition for this resource. The wood price in comparison was relatively stable during the season. 73 % of the respondents used only wood as an energy source in BM while the remainder uses both wood and compacted dung.

The change ratio of the inputs prices was higher than that of the output prices. At the onset of the season the prices of loose and compacted dung were low and the brick price was high. Thereafter dung prices increased and brick prices declined as a consequence of raising production (Table 2).

The Average Product (AP) of red bricks varied with input quality whereby the AP of loose dung ranged from 2950–4660 bricks per t DM and compacted dung burning yielded between 2490–4980 bricks per t DM. For wood AP ranged from 25,710–180,000 bricks per t (Table 3). Cost benefit calculations showed that 57 % of total expenses were labour costs while loose dung costs amounted to 22 %, fuel wood costs to 13 %, and land rent to 6 %. The B/C ratio for red BM was 1.25 SDG for every SDG invested (Table 4).

3.3 *Income distribution among farmers and red brick kiln owners*

Household incomes differed greatly, reflecting differences in family activities. Farmers and kiln owners generated different incomes from *Gerif* land leading to per capita incomes that averaged 2.4 SDG per day for farmers and 13 SDG per day for kiln owners. With a Gini coefficient of about 0.38 the income of red brick kiln owners was more equally distributed than of the farmers (Table 5). However, despite the higher return the B/C ratio of BM was lower than that of urban farming activities.

The share of land rent in total costs varied almost five-fold among farm and BM households.

Table 3: *Average Product (AP) in 1000 bricks t^{-1} of loose and compacted dung and 1000 bricks per t^{-1} of wood among sampled kiln owners (n = 49) in Khartoum, Sudan, 2009. Data show means followed by their standard deviation.*

Parameter	*% of kiln owners*	*Mean*
Loose dung AP	86	3.706 (0.4235)
Compacted dung AP	27	4.056 (0.7728)
Wood AP	100	45.345 (99.5687)

Table 4: *Average cost, average return, and benefit cost ratio (B/C) in SDG* * *per 1000 bricks for sampled farmers (n = 44) in Khartoum, Sudan, 2009.*

Parameter	*Mean*
Rent cost	4.0
Total labor cost	39.0
Cost of loose dung	15.0
Cost for biomass fuel	9.0
Other Cost	1.5
Average revenue	85.2
Average cost	68.0
Net revenue	17.2
B/C	1.25

* SDG (New Sudanese Pound) ≈ 0.4 US$

Table 5: *Average net return, total return, and total cost for farms and kilns (in SDG* **), Gini coefficient, benefit cost ratio (B/C), and land share of total cost for farms and kilns in urban Khartoum, Sudan, 2009.*

Parameter	*Red brick kiln owners* (n = 45)	*Urban farmers* (n = 15)
Average total return	147,229.60	8,267.00
Average total cost	116,355.30	3,718.20
Average net return	30,874.3	4,626.00
Gini coefficient	0.38	0.49
B/C	1.27	2.22
Land share of total cost (%)	6.00	29.00

* SDG (New Sudanese Pound) ≈ 0.4 US$

3.4 *Biomass consumptions and GHG emission*

At the time of the study the price of one bag (50 kg) of urea (46 % N) and TSP (triplesuperphosphate, 20 % P) was 65 SDG, while prices of the equivalent amounts of N were 70 and 27 SDG from loose and compacted dung and were 107 and 29 SDG of P from loose and compacted dung, respectively. Alternatively, the price for 1 bag (50 kg) of NPK (18:18:5) was 150 SDG while the equivalent amounts of nutrients from dung was 31 SDG for loose dung and 8 SDG for compacted dung.

Average amount of C_{org} varied from 354 ± 4.2 to 276 ± 29.1 $g\,kg^{-1}$ DM, in loose and compacted dung, respectively while the K concentration in compacted dung (33 ± 2.0 $g\,kg^{-1}$ DM) was 153 % higher than in loose dung (13 ± 2.0 $g\,kg^{-1}$ DM). For N and P concentrations slight difference were found between loose and compacted dung (Figure 2).

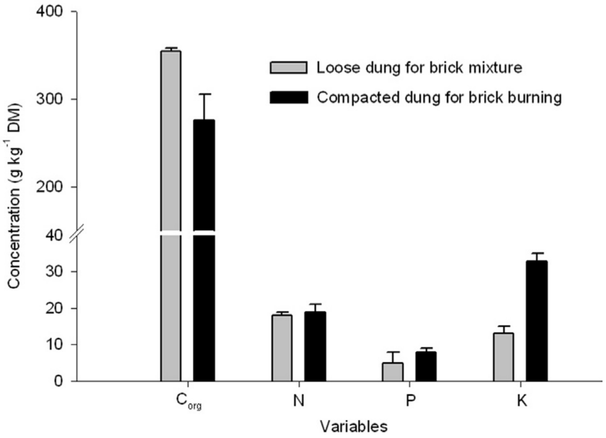

Fig. 2: *Average concentrations of organic carbon (C_{org}, n = 5), nitrogen (N, n = 5), phosphorus (P, n = 10), and potassium (K, n = 10) in loose and compacted dung used in red brick kilns of Khartoum, Sudan, 2009.*

The capacity of one dung-filled lorry used in BM production was about 6.5 t DM and 24 t DM of loose and compacted dung, respectively, with a density of 0.31 $g\,cm^{-3}$ and 1.14 $g\,cm^{-3}$. The annual DM consumption of loose dung exceeded that of compacted dung by almost 20 % yielding on average 1,677,000 bricks (Table 6). Overall wood consumption for BM was much lower than dung consumption, but still the consumption of fuel wood from the annual wood harvested was equivalent to 53 % of the round wood and the rest was branch wood (Table 7).

The comparison of our estimates of GHG emissions in kiln-based BM from loose and compacted dung based on the IPPC approach versus actual values obtained from the labouratory analysis for the dung samples yielded very different results (Table 8).

According to our analyses, average C concentration of the dung was about 35 ± 0.4 % for loose dung and 28 ± 2.9 % for compacted dung. Average N/C ratio was about 0.05 ± 0.002 and 0.07 ± 0.003 for loose and compacted dung, respectively, and the fraction of biomass oxidized was 0.68 ± 0.016 and 0.55 ± 0.057. Consequently, the TC_r, CO_2, CO, and CH_4 emission of cow dung estimated from the IPCC default values exceeded the values derived from measured data by about 40 % and 60 % for loose and compacted dung. The opposite was true for NO_X, NO, and N_2O for which the calculated values were 3-fold and 2,5-fold the IPCC values for loose and compacted dung, respectively. As a consequence of the low consumption of wood in BM, emissions from fuel wood were much lower than emissions from cow dung (Table 8).

Table 6: *Average amounts of dry matter (DM), organic carbon (C_{org}, n = 5), nitrogen (N, n = 5), phosphorus (P, n = 10), potassium (K, n = 10) contained in cow dung used in red brick kilns (n = 49) in Khartoum, Sudan, 2009.*

Variables	*Consumption of loose dung*		*Consumption of compacted dung*	
	kg per 1000 bricks	*t per year of brick production*	*kg per 1000 bricks*	*t per year of brick production*
DM	270	475	247	381
C_{org}	95.6 (1.14)	168.1 (2.01)	68.1 (7.18)	105.3 (11.10)
N	4.9 (0.25)	8.6 (0.45)	4.6 (0.47)	7.1 (0.72)
P	1.4 (0.08)	2.4 (0.14)	1.9 (0.23)	2.9 (0.35)
K	3.5 (0.55)	6.2 (0.97)	8.2 (0.41)	12.6 (0.64)

Average brick production per year = $1,677 \times 10^3$

Table 7: *Average amounts of fuel wood used in red brick kilns (n = 49) of Khartoum, Sudan, 2009.*

Production of bricks	*Wood consumption* (t DM)	*Round wood* (m^3)	*Total harvested wood* (m^3)
1000 bricks	0.02 (0.001)	0.03 (0.002)	0.06 (0.004)
Bricks per year	36 (3.5)	56 (5.4)	106 (10.2)

Average brick production per year = $1,677 \times 10^3$

Table 8: *Total carbon released* (TC_r) *and emissions of greenhouse gases (GHGs) from loose and compacted dung and fuel wood consumed in red brick kilns in Khartoum, Sudan, 2009.*

Biomass consumption	TC_r	*GHG emissions*						*Total emission*
		CO_2	CO	CH_4	NO_X	NO	N_2O	
Loose dung		*Based on IPCC default values*						
kg per 1000 bricks	109	372	15	1.75	0.43	0.28	0.01	390
t year $^{-1}$	192	656	27	3.08	0.76	0.50	0.02	688
		Based on own data						
kg per 1000 bricks	65	222	9	1.04	1.33	0.87	0.04	234
t year $^{-1}$	115	391	16	1.83	2.34	1.52	0.06	413
Compacted dung		*Based on IPCC default values*						
kg per 1000 bricks	100	340	14	1.60	0.40	0.26	0.01	357
t year $^{-1}$	154	523	22	5.47	0.61	0.40	0.02	548
		Based on own data						
kg per 1000 bricks	37	128	5	0.60	1.01	0.66	0.03	135
t year $^{-1}$	58	196	8	0.93	1.56	1.02	0.04	208
Fuel wood		*Based on IPCC default values*						
kg per 1000 bricks	10	34	1	0.16	0.04	0.03	0.001	35
t year $^{-1}$	16	58	2	0.26	0.06	0.04	0.002	60

4 Discussion

Given the scarcity of *Gerif* soils and alternative land use options, land owners in Khartoum have the choice of renting their land out either for share cropping or BM. Such competition and interaction between agriculture and brick kilns has been reported previously from Vietnam (Jensen & Peppard Jr, 2004), Pakistan (Ishaq *et al.*, 2010) and Sudan (Alam & Starr, 2009). It leads to a frequent modification of the spatial land use pattern following changes in opportunity costs for land and labour (Sazak, 2004; Singh & Sarfaraz Asgher, 2005; Muto, 2006; Lankoski & Ollikainen, 2008; Schumacher *et al.*, 2009). The seasonality of rainfall and of the height of the River Nile waters leads to additional temporal variation of land use (Jensen & Peppard Jr, 2004; Thompson *et al.*, 2010). Our survey indicated that red BM is more profitable at the beginning of the season rather than at mid-season when most kilns are fully operating. During the former period input prices, mainly dung, are low because of low demand while brick prices are high due to the proximity of the inactive kiln season. Limited opportunity costs for cow dung in agriculture that benefits from the fertilizing floods of the River Nile make the BM activity of great interest to animal producers through the provision of extra income (Omer & Fadalla, 2003). The B/C ratio is higher in crop production than in red BM, but limited land area and higher cost of inputs used are constraints to agricultural production.

Red BM provides employment opportunities and, as indicated by the low Gini coefficient, secures a more even distribution of income among kiln owners (Singh & Sarfaraz Asgher, 2005). This leads to the continuous expansion of this industry at the expense of agricultural activities along the Blue Nile and the River Nile regardless of the associated environmental problems for the surrounding populated and crop growing areas (Jensen & Peppard Jr, 2004; Sazak, 2004; Muto, 2006).

Currently cow dung in Khartoum state is only used as a fuel for BM activity rather than for agriculture where mineral fertilizers are applied if farmers consider it necessary (Omer & Fadalla, 2003; Alam & Starr, 2009). Our data indicate that per unit N and P applied, compacted cow dung is cheaper than mineral fertilizers. Even though, farmers prefer to apply urea or compound mineral fertilizers because of the faster availability of N compared to manure. In a companion study on partial nutrient balances in urban *Gerif* land of Khartoum Abdalla *et al.* (2012) reported annual surpluses of 239 kg N ha^{-1} and 3,621 kg C ha^{-1}, and deficits of 32 kg P ha^{-1} and 403 kg K ha^{-1}. If the compacted dung used for BM was instead applied as a soil amendment, annual projected horizontal surpluses would be 1,236 kg N ha−1, 397 kg P ha^{-1}, 1,494 kg K ha^{-1}, and 18,447 kg C ha^{-1}. The 36 t of annual fuel wood consumption for BM in Khartoum are comparable to that of about 5.3 million inhabitants (Central Bureau of Statistics, 2009).

Sudan's national GHG inventory of 1995 (MEPD & HCENR, 2003) reports total emissions of about 25,752,000 t consisting of 20,077,000 t CO_2, 3,280,000 t CO, 1,985,000 t CH_4, and other gases such as NMVOC, NO_X, N_2O, HFCs, and SO_2 of which 78 % was emitted as CO_2. Using the IPCC (1996) approach, estimated annual gaseous emissions of 2000 brick kilns in Khartoum state (Alam & Starr, 2009) contributed 10 % and wood burning kilns another 0.5 % to total emissions. This rather large share reflects the high urbanization-driven demand for construction materials (Tahir *et al.*, 2010). Similar to the finding of Alam & Starr (2009) GHG emissions from biomass fuel (cow dung and wood) was dominated by CO_2, CO, and CH_4 followed by non-carbon gas emissions.

According to the IPCC (1996) the aboveground biomass of tropical forests in African compacted zones (rainfall $<$ 1000 mm $year^{-1}$) ranges from 20 to 55 t DM ha^{-1}. As the average rainfall in the dry zone of Sudan ranges from 100 to 300 mm $year^{-1}$ (Hamad & El-Battahani, 2005; Mubarak *et al.*, 2010) we assume the aboveground biomass of local forests are at the lower range (20 t DM ha^{-1}). Based on this a wood consumption of 36 t DM $year^{-1}$ would translate to about 2 ha $year^{-1}$ deforested area.

5 Conclusions

Kiln-based BM on the fertile flood land along the Nile and its tributaries has profound effects on the spatial and temporal land use pattern in Khartoum and offers income opportunities for a significant number of kiln owners and their employees. Although the manure- and wood-based production of red bricks contributes substantially to the income of kiln owners, improvements in energy use efficiency may allow kilns to reduce GHG emissions per unit brick, while increasing the overall profitability of this land use system (Schilderman, 2002). The preliminary information about the GHG emissions in this study could be used for further research in order to better assess emissions from different brick mixtures and brick kilns. There also may be a need to raise farmers' awareness about the benefits of cow dung to maintain C_{org} levels in intensively cultivated *Gerif* soils in Khartoum.

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