Waste Biomass to Charcoal Briquettes in Tanzania

Regional Supply Potential – REPIC Project Report

EFCO Emmental Forest Cooperation

UNIVERSITÄT BERN

CDE CENTRE FOR DEVELOPMENT AND ENVIRONMENT

Report to the Renewable Energy, Energy and Resource Efficiency Promotion in Developing and Transition Countries (REPIC) – Contract # 2016.08

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1 Introduction

1.1 Context

Wood-based cooking fuels, notably firewood and charcoal, are currently the most widely used cooking fuel in Tanzania (NBS and REA 2017). However, wood is being sourced often in an unsustainable way leading to environmental degradation or local supply shortages (Mwampamba 2007; Ghilardi et al. 2009; Ahrends et al. 2010). Currently, policies focus mainly on fossil based cooking fuels alternatives such as LQP or paraffin. However, these fossil fuels contribute to increasing CO2 levels in the atmosphere and thus to global warming. Furthermore, charcoal is a major income opportunity for poor rural households and it unlikely that fossil cooking fuels could fully replace this income opportunity.

A promising alternative to firewood - and notably to charcoal - are char dust briquettes. Char dust briquettes are briquettes from carbonized biomass – typically biomass waste. In line with the wide range of the possible biomass input, a wide range of briquette production technologies exist (Scholz et al. 2014; Asamoah et al. 2016). From an economic point of view, studies show different and sometimes contradicting findings. On the one hand, for instance, it has been claimed that the average cost per energy output of briquettes is more than twice than that of charcoal (Tumutegyereize et al. 2016) but on the other hand, that briquettes are in a price range that makes them competitive with charcoal. (Okoko et al. 2018). From an ecological point of view, studies agree fairly well on the advantages of consumption of char dust briquettes. They have the potential to lower the carbon footprint (Njenga et al. 2014; Okoko et al. 2017), help alleviate environmental degradation (Njenga et al. 2013; Njenga et al. 2014; Bär et al. 2017), can increase access to renewable energy (Njenga et al. 2013), and provide new income opportunities (Ngusale et al. 2014).

Despite the above-mentioned advantages and potentials, the use of char dust briquettes for cooking in Tanzania (NBS and REA 2017) and in sub-Saharan Africa (Kammila et al. 2014; Kappen et al. 2017) is very marginal. Multiple studies have examined challenges that might present explanations to this low use of briquettes, but also opportunities related to improve production, marketing, and consumption of briquettes (Mwampamba et al. 2013; Ngusale et al. 2014; Njenga et al. 2014; Scholz et al. 2014; Asamoah et al. 2016; Lohri et al. 2016). Asamoha et al. (2016), for instance, have identified multiple drivers to success and challenges faced by briquette business. Main drivers to success are the cost and availability of competing fuels, policy regulations, partnerships, consistency in the quality and supply of briquettes, the appropriate targeting of consumers, securing contacts with partners, and an effective marketing strategy coupled with a good distribution system; the main barriers comprise regulatory barriers, financial barriers, and operational and market-related barriers.

1.2 The “Waste Biomass to Charcoal Briquettes in Tanzania” project

The REPIC co-funded project “Waste Biomass to Charcoal Briquettes in Tanzania” (WBCBT) launched in September 2016. The overall goal was to promote charcoal production based on waste agricultural and forestry biomass as a substitute for deforestation-based (conventional) wood charcoal. The project is split into three project Phases (I-III) with respective goals of:

I. Demonstrating proof of operational concept (initial 6 months): Establish a pre-commercial start-up enterprise and begin production of charcoal dust (char dust) using available technology. Process the dust into charcoal briquettes with project partners ARTI (Appropriate Rural Technology Institute; http://arti-africa.org/) and their commercial spin-off

CBTL (Charcoal Briquettes Tanzania Ltd.), and bring a sample of these briquettes to market to test consumer perceptions.

II. Demonstrating proof of economic concept (months 6 to 30): Achieve economic proof of concept by upscaling and optimizing production to achieve a targeted selling price that rivals conventional charcoal. Develop a tracking and certification system with project partners TruTrade Ltd based on their “Transaction Security System” (TSS) to ensure transparent and environmentally sustainable production. Bring an economically viable production volume to market (at least 320 tons of briquettes) over the 2 year period.

III. Environmental/socioeconomic impact assessment and business plan development (months 18 to 30): Model and assess the environmental and socioeconomic impacts of upscaling using scenario analysis calibrated to data collected in the field and from our pilot enterprise. Investigate potential income and employment effects for rural landowners and youths and investigate the regional availability (supply) of biomass. Consolidate findings into a business plan to be disseminated to investors, donors and entrepreneurs to multiply the project impacts.

Figure 1. Overall concept behind the WBCBT project, showing how harvest waste biomass is converted to charcoal briquettes and sold to urban consumers for their cooking energy needs (thus substituting conventional wood-based charcoal)

1.3 Objective and outputs

The overall objective of this report’s work is to estimate the potential feedstock for char dust briquettes production in order to provide the base data for the above-mentioned goal III of upscaling. Table 1 provides an overview of the more specific objectives and their related deliverables.

Table 1: Objectives and deliverables

Objectives	Deliverables
Overall: Estimate the potential feedstock for char dust briquette production (crop residues and off-cuts from trees) in the WBCBT project	Report presenting research method and results (see specific objectives and results below)
Specific: 1) Modelling the economically viable supply catchment for the char dust briquette production site in Magunguli	Overview maps or the supply catchment and its surroundings (delineation, villages/towns, roads, terrain) in GIS format.
2) Modelling the current land cover and use within the supply catchment.	Land cover/use map in GIS format.
3) Estimating the potential supply of feedstock within the supply catchment	Supply potential map and total supply potential of the feedstock in GIS format.
4) Repeat step 1 for potential upscaling scenarios of new production facilities in the larger supply catchment area (the location of the sites will be identified in consultation with the EFCO project team)	Map with alternative production facilities and the surrounding potential for feedstock in GIS format

In a final step in this report, the findings are put into context with the results from other Phases of the project, namely the experience gained through business model development. To do this, we combine production data on briquette production (costs, employment, output etc.) with biomass availability to assess the potential for upscaling the concept. Through the construction of numerous "upscaling scenarios", we estimate potential socio-economic and environmental impacts resulting from broader uptake of the technology.

2 Methods

2.1 Case study area

The study perimeter for this work is an area of 100 x 100 km around pilot production facility, which is located close to the village of Magunguli in the Southern Highlands of Tanzania (cf. Figure 2). The area covers entirely the districts of Mafinga Township and Makambako Township, and partly the districts of Mufindi, Wanging'ombe, Njombe, Mbarali, and Kilombero. The landscape is characterised by the highland in the North and West, which is rather flat and reaching an altitude up to 2000 m, a scarp, spreading from the West to the East, which has a steep gradient between 1800 m and 1300 m, and the low land in the Southwest, which is characterized by a hilly terrain and gradually descends to an altitude of 500 m.

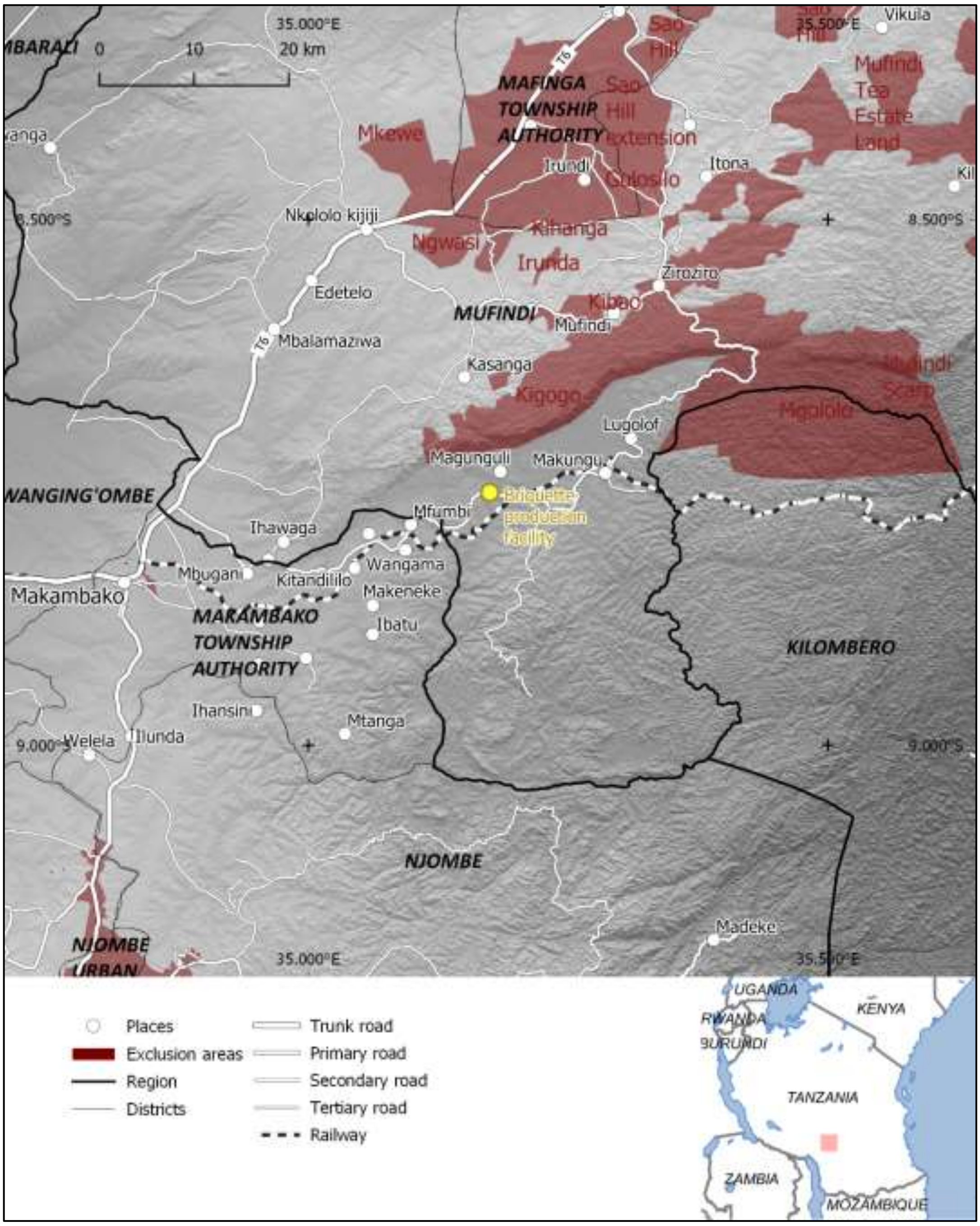

Figure 2: Overview of case study area

The production food crops and the wood are the dominant productive land use types in the study perimeter. Smallholdings cover the most of the productive land cultivating mainly maize and managing private forest plantations. Government institutions and private large-scale enterprises, however, own and manage waste areas consisting mostly of forest plantations, tea plantations, and protected forest reserves.

The closest potential target marked is Makambako. The town has a population of approximately 90,000 inhabitants and is located approximately 50 km west of the pilot production facility. Other potential market are Njombe and Mafinga. Njombe has a population of approximately 130,000 persons and is located 60 km south of Makambako; Mafinga has a population of approximately 50,000 persons and is located 85 km northeast of Makambako. Both towns are situated outside the actual study area, but are potential target markets due to the proximity to case study perimeter and the good road infrastructure (paved trunk road T6) connecting them with Makambako and hence the pilot production facility.

2.2 Approach

The approach to model the regional supply potential consists of four main work packages: 1) the land classification, 2) the biomass estimation, 3) the scenarios of biomass harvesting and briquette production, and 4) the impact assessment. The main corresponding outputs are a land classification map presenting the different land classes of the case study areas, a biomass map presenting the potential biomass supply from crop field and forest plantations, and a production facility map that indicates potential sites for new briquette production facilities. Figure 3 gives an overview of the different work steps; the following sections describe these work steps in more detail.

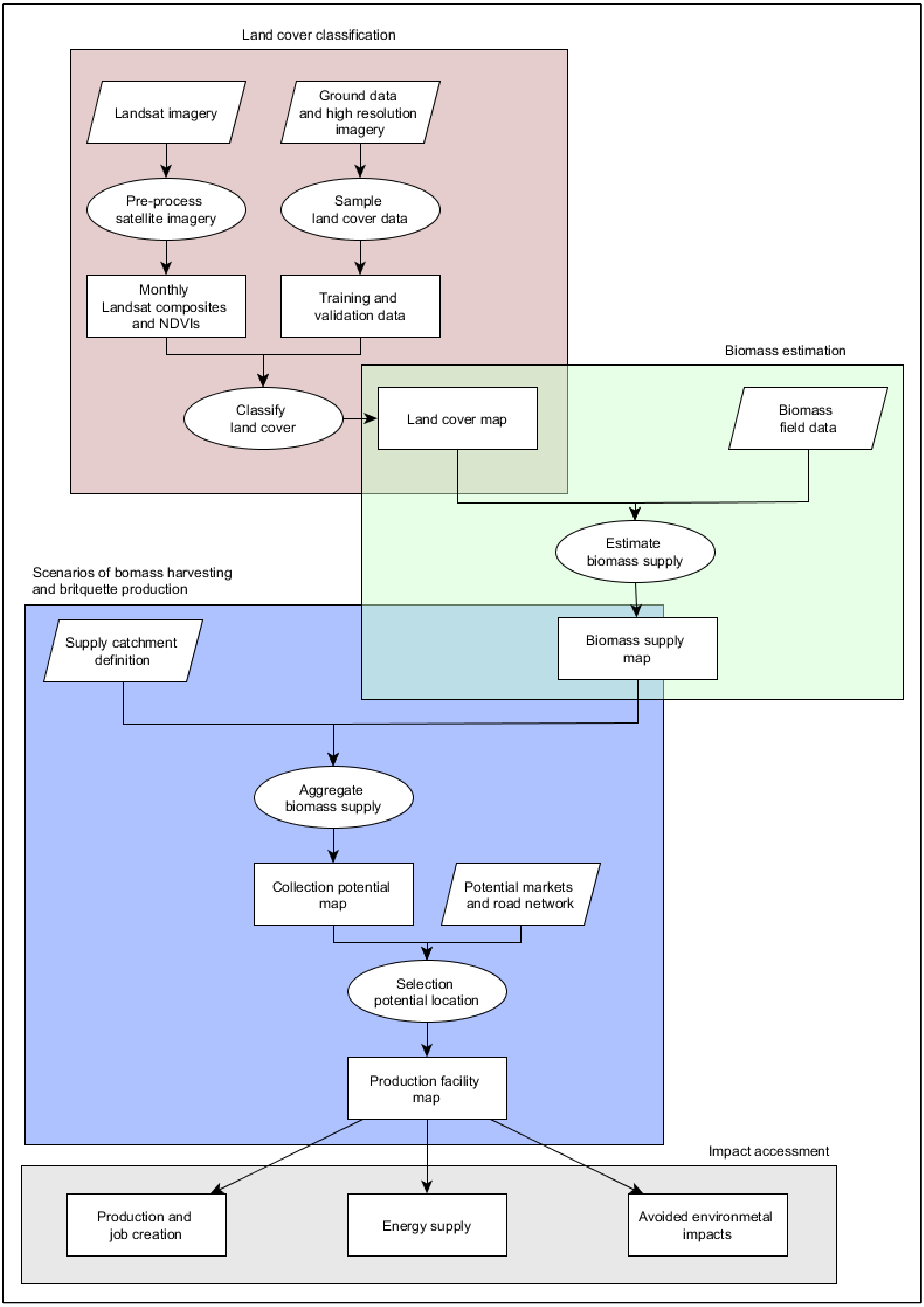

Figure 3: Overview of the modelling approach
(parallelogram = input; oval = work step; rectangle = output))

2.3 Land classification

2.3.1 Acquisition and pre-possessing of satellite imagery

The land classification uses Landsat imagery and its derived NDVI layers as input base data. In a first step, we created monthly Landsat composites for the time between November 2015 and October 2018. In a second step, we created a Normalized Difference Vegetation Index (NDVI) layer for each Landsat composite image.

For the creation of the monthly Landsat composites, we used the Google Earth Engine Image Pre-processing Tool[1] developed by the Centre for Development and Environment (Hurni et al. 2017). The tool allows:

1) downloading Landsat imagery for a given area and time period
2) pre-pre-processing the images by applying a cloud masks and convert the images to top-of-atmosphere (including topographic correction)
3) creating a mosaic using the pre-processed images

No data cells where subsequently set to -9999.

For each Landsat composite, we calculated the Normalise Difference Vegetation Index (NDVI) calculated as follows:

$$NDVI = \frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + \mathrm{Red})}$$

where red and NIR stand for the spectral reflectance values in the red and near-infrared regions, respectively. The NDVI layers where computed using R (cf. Appendix: 6.1).

2.3.2 Land cover data sampling

Land cover classes

We distinguished between nine different land cover classes. Crop fields and forest plantations are the relevant land cover types the potential supply of biomass residues. The remaining seven land cover classes were included in order to improve the accuracy of the classification. However, classification errors concerning these latter classes, i.e. class confusions among them, will not concern the biomass estimations. Table 2 provides an overview of the nine land cover classes including a description and sample images of each class.

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[1] http://www.cde.unibe.ch/research/projects/a_tool_for_satellite_image_preprocessing_and_composition/index_eng.html

Table 2: Land cover classes

Class	Description	Sample points	Photo (Field data)	High-resolution satellite imagery (GoogleMaps)
Crop field (c)	Plots for food crop production. Mostly maize.	281		
Forest plantation (fp)	Private forest plantations. Smallholder only. Mostly Pine and Eucalyptus	220		
Dense natural forest (fd)	Natural forest. Closed canopy cover	185		
Sparse natural forest (fl)	Natural forest. Open canopy cover	204		
Urban / bare (bu)	Areas or urban areas	56		

Bushland (b)	Bushland. Woody vegetation. Maximal height of approximately 4 meters.	217		
Grassland (g)	Grassland. Herbaceous vegetation only.	181		
Waterbody / wetland (ww)	Lakes, reservoirs, ponds, and wetlands	165		
Tea plantation (t)	Tea plantations. Always large-scale owner.	26		
Total		1526		

Sample data for these land cover classes where obtained from two different sources. On the one hand, we collected ground truth data during the field word; on the other hand, we derived sample data from high-resolution satellite imagery. Figure 4 provides an overview of the spatial distribution of all land cover sample points.

Ground truth sampling

The ground truth sampling consists of the collection of land use pictures, the classification of these images, and the subsequent geo-localisation. We took 320 land cover pictures including their geographical coordinates and view direction. After a first classification in the field, we reclassified the pictures according above-presented land cover classes. Finally, we created a new sample point layer with the land cover identified in the picture and the corrected coordinates based on the coordinates of the picture and the view direction.

Imagery sampling

The imagery sampling is based on visual interpretation of high-resolution satellite imagery services (i.e. GoogleMaps, Bing maps, ESRI satellite, Yandex satellite). We first created 1215 sampling points following a random stratified sampling approach. For this purpose, we use an existing, coarse land cover map providing the strata for the sample point distribution. Table 2 shows the number of sample points per land cover class. In order to avoid duplicated samples (i.e. multiple sample points within the same Landsat raster pixel), we ensured a minimal distance of 50 m between the sample points. After the first classification and validation runs, we complemented the imagery sampling data set with class specific samplings in order to reduce classification class confusion between the relevant classes.

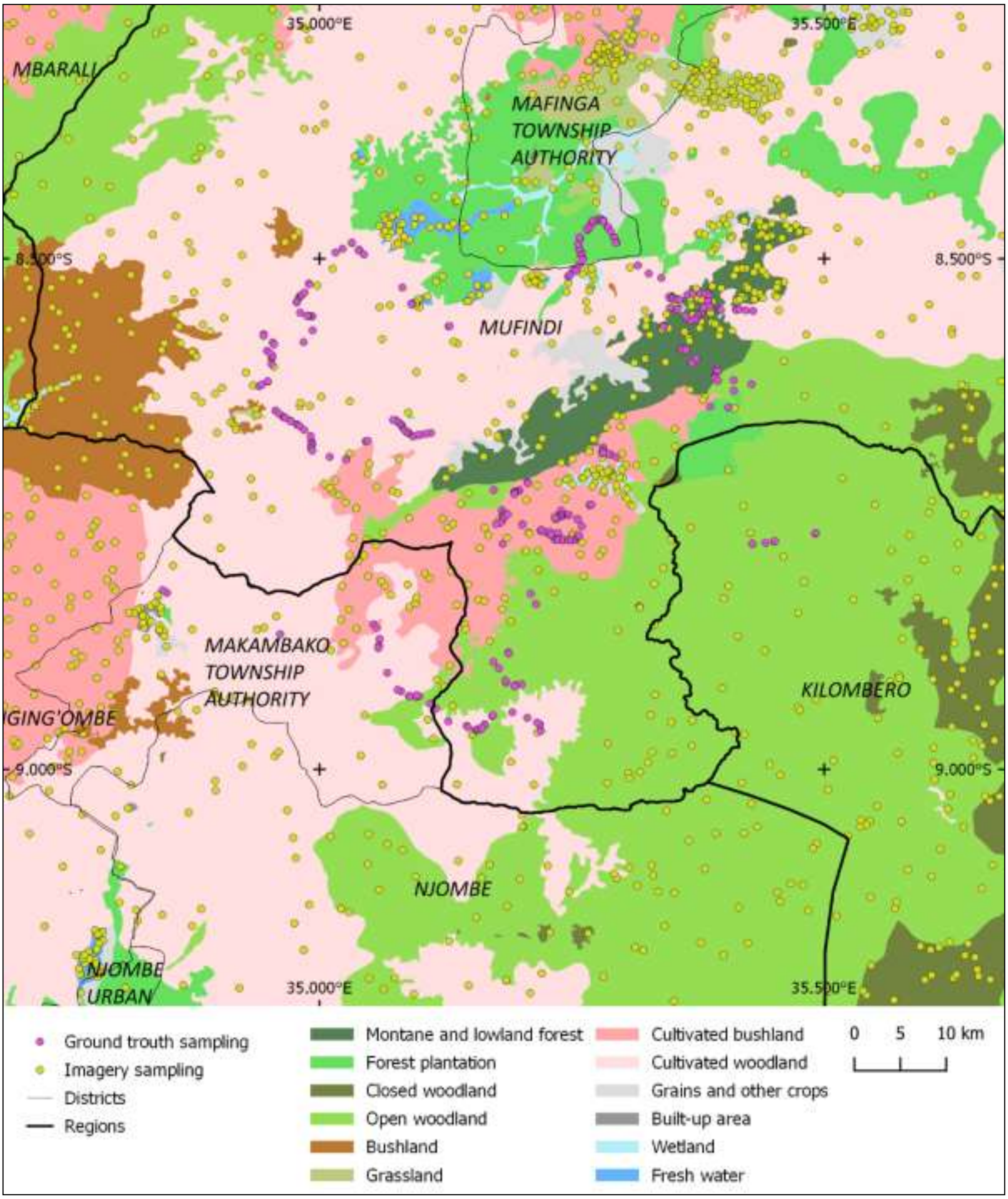

Figure 4: Land cover sample points

2.3.3 Land cover classification

Classification

We ran the land cover classification based on pre-processed satellite imagery and the collected land cover sampling data using the Random Forest algorithm (Breiman 2001). Beforehand, we split the sampling data randomly into training and validation data by a 70-to-30 ratio. The corresponding R script can be found in Appendix 6.1.

Exclusion areas

After the completion of the land cover classification, we defined manually exclusion areas. Such exclusion areas comprise protected areas (Game controlled areas and forest reserves) and large forest plantations owned by the government or private firms. These areas were considered not to be potential biomass supply areas and there for excluded from the analysis at a later stage.

We obtained the exclusion from the World Database of Protected Areas (UNEP-WCMC 2018). The perimeter of the areas where subsequently retraced based on the visual interpretation of high-resolution satellite imagers (i.e. GoogleMaps, Bing maps, ESRI satellite, Yandex satellite) in order to adjust the accuracy to the spatial resolution of the case study site's spatial scale and to complemented missing areas.

2.4 Biomass estimation

2.4.1 Sub-plot sampling strategy

Sampling was carried out at the field or forest stand level. Two strategies were pursued:

1) In the ideal case, 5 sub-plots of 5 x 5 m area were set up largely at the centre of each field/forest stand. The distance to edge, where visible from the plots, was recorded. In one case, deep in a forest stand, the distance was not recorded (data entry = "NA"). The 5 plots were generally set up to resemble a circle, with 4 plots placed in the 4 quadrants of the circle and a fifth in the centre. The aggregate of these sub-plots is referred to as a plot.

Figure 5. A biomass sampling subplot of 5m x 5m within a maize field

2) In another set of cases, fields were already being cleared for planting in the next season. In these cases, biomass could not be localized on field, as piles of biomass had already been prepared by the farmers. Therefore, we measured biomass amounts across the entire field. This allowed a much larger area to be sampled, but lacked any Plot-SubPlot hierarchy. Therefore the sum of biomass for the entire field is simply referred to as the Plot.

2.4.2 Aggregation of sub-plots

Because two sampling strategies were performed with two different levels of detail, aggregation was necessary to the coarsest scale. Therefore and to facilitate uniform comparison, the sub-plot data were all aggregated to a single plot number (i.e. all biomass and area summed together).

2.4.3 Calculation of dry weight

From the aggregate data on area and biomass amounts (in kg), biomass density was estimated in the following way: 1) Biomass weight was converted to dry weight using two approaches, the “green” moisture content (MC) approach and the “brown” moisture content approach. For the green MC approach, moisture content is simply expressed as a fraction of the total weight, therefore dry weight is calculated by taking away this fraction from the total weight:

Dry weight = Total weight*(1-Moisture content(%)/100)

For the brown MC approach, moisture content is expressed as a percent of the dry weight (i.e. the ratio water to dry weight in the total biomass):

Dry weight = Total weight/(1+(Moisture content(%)/100))

We used simple moisture meters that are available at typical DIY suppliers for assessing the moisture content of wood and other biomass. There was no information on the type of moisture content (%) that was calculated (green or brown), therefore we calculated both versions. For the simple instruments used, we believe the estimate would generally follow the “green” approach, as the “brown” approach is more industry specific and specialized for larger scale equipment. The outcome of calculations are very similar, but the “green” approach usually estimates slightly lower values.

2.4.4 Forestry aggregation over time

In order to get an accurate picture of the forestry biomass, the following considerations are needed: 1) litter biomass is available only in pine forests, and can be collected each year. 2) Pruning biomass from cutting the low lying branches is only relevant in 3rd and 4th year of the plantation. 3) Finally, the harvest biomass was not estimated here because weighting this was unfeasible. Thus, for all harvest waste estimates, we resort to literature data. To get an accurate picture of the total biomass per year, one needs to calculate:

Total biomass per year (kg/m-2 y-1) = (Litter biomass (kg/m-2 y-2) + [(pruning 3rd year (kg/m-2) + pruning 4th year (kg/m-2) + harvest waste (kg/m-2)) / age of plantation at harvesting (y)]

This will give the lifetime average of a single stand of trees. For eucalyptus stands, there is no real pruning or litter waste that is suitable, only the harvest waste.

2.4.5 Estimation of land cover class productivity

We estimated the biomass supply potential of forest plantations and crop field by simply calculating the mean dry weight density for the respective land use type. Subsequently, we assigned these values to the raster cells to the crop fields and forest plantation by multiplying the dry weight density with the cell size.

Figure 6. Different biomass types: a) pine needles, b) harvest waste from forestry, c) collected harvest waste from a potato field and d) harvest waste from maize being weighted by field assistants

2.5 Scenarios of biomass harvesting and briquette production

During the project, we developed a pilot enterprise for briquette production (see Case study area descriptions, section 2.1). This facility was designed to achieve technical proof of concept, and identify the conditions for economic profitability in briquette production. Based on the observed production processes, we developed a baseline “observed” production scenario (i.e. business model including all costs and income of the enterprise). We then developed as “optimized” scenario encompassing potential improvements of the facility within the bounds of the chosen technology (custom-built briquette press) and local constraints (lacking electricity, water facilities, transport costs, binder availability etc.).

However, for developing the regional scenarios of upscaling production across the region, the pilot enterprise did not reflect efficient production at scale with optimal access to infrastructure (water, electricity, transport etc.). Therefore, we developed two additional and separate scenarios of biomass collection and briquette production using upscaled production methods. We assumed a “decentralized” briquette production model and a “centralized” model.

1. Decentralized upscaled production: In this scenario, facilities were placed in suitable areas in the landscape to harvest the most available biomass (see below for criteria). 20 facilities were hypothetically placed in the landscape with at least a 5 km buffer distance around each facility. Char dust is assumed to be purchased locally and briquettes are sent to market.
2. Centralized upscaled production: In this scenario, briquette pressing was assumed to be centralized with biomass collected in larger amounts by truck, purchased of rural producers of char dust. We assume that all biomass is available for harvest within 5 km of a tertiary or larger road. Briquette pressing occurs in the urban market and the product is sold directly to consumers.

For both upscaling scenarios, we combined data observed in the field (i.e. in biomass conversion efficiencies, char dust weight and conversion factors, local wages etc.) with additional data from larger-scale producers (ARTI Tanzania, pers. comm). Thus these hypothetical models are anchored in realistic assumptions and parameters. All production model scenarios are presented in Appendix 0.

Decentralized scenario site selection for hypothetical new facilities

We based site selection for briquette facilities on the amount of available biomass within an economically-viable collection distance. We first created a supply potential map by calculating for each cell the total sum of biomass productivity with a radius of 5 km. In other words, we assumed each cell to be a potential site for a production facility and calculated the potential biomass supply from crop fields and smallholder forest plantations that are within a reasonable distance. In consultation with local partners, we manually placed 20 such facilities in the best areas of the landscape to harvest biomass, considering also a minimum connection to a minor road (to transport briquettes to market).

The choice of 5 km as the maximal distance for biomass collection is based on the experiences at the pilot production facility, where the transport of char dust from collected biomass was usually carried out by tractor and trailer and rarely exceeded a distance of 5 km as the bird flies. In a second step, we estimated transport costs of a second-hand tractor and trailer similar to what is available in the study region using the Excel based tool “TractoScope” (Agroscope, Institut für Nachhaltigkeitswissenschaften INH, Tänikon - V. 5.1/2015). This tool estimates machine costs for a variety of machines based on a set of database parameters, which can be adjusted by the user (e.g. fuel use, motor use intensity, repair costs, new/second hand and purchase price).

We adjusted these parameters to reflect the local machine and context, but assumed a larger trailer than what was locally available, to reflect the potential for upscaling. Based on a separate economic model of the local production facility and its potential for upscaling (see Appendix), we arrived at a maximum one-way transport distance of 12.5 km to facilitate two loading trips to collect char dust per day. This would certainly lie under 10 km as the bird flies. Therefore a maximum range of 5 km is realistic both from our practical experience in the field, and from the consideration of economic costs of char dust transport.

Centralized scenario biomass harvesting and briquette production

For the centralized production, we adjusted the transport costs even further to account for truck transport of char dust to the urban markets. We then assumed that all biomass within 5 km of a tertiary road is available for conversion into char dust by char dust producers. Otherwise the assumption of briquette technology and production is identical in the two scenarios. What differs is the total amount of biomass harvestable and the location of job and income creation.

Table 3. Biomass collection and briquette production scenarios for the impact assessment of upscaling

Scenario	Description	Briquette production system
Decentralized	20 rural briquette facilities along roads, delivery of briquettes to market towns	Upscaled production with briquette press of 2 tonne per day capacity and facility and adjusted fixed and variable costs (ARTI Tanzania, pers. comm.), combined with local cost and logistics data from this study
Centralized 25%	Centralized briquette facilities in market towns that capture 25% of biomass within 5 km of road (char dust transport via lorry)	
Centralized 50%	Centralized briquette facilities in market towns that capture 50% of biomass within 5 km of road	
Centralized 75%	Centralized briquette facilities in market towns that capture 75% of biomass within 5 km of road	
Centralized 100%	Centralized briquette facilities in market towns that capture 100% of biomass within 5 km of road	
Combination 65%	20 decentralized facilities (40% of total), centralized collection for further 25% along roads	
Combination 100%	20 decentralized facilities (40% of total), centralized collection for further 50% along roads	

3 Results

3.1 Land cover classification

3.1.1 Land cover

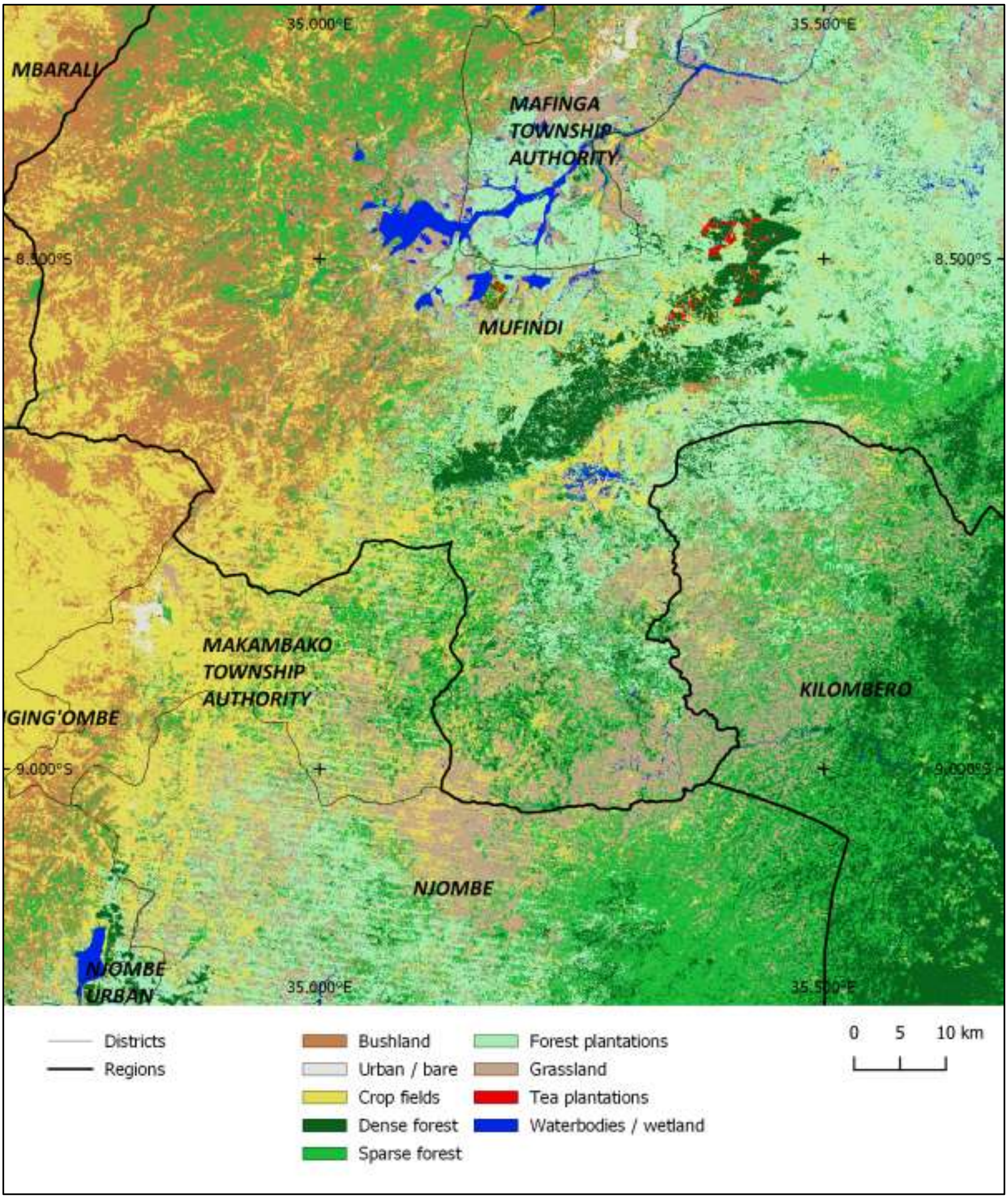

Figure 7: Land cover map in the case study area

Figure 7 shows the classified land cover in the case study areas. The maps distinguishes between bushland, urban / bare areas, crop field, dense and sparse forest, forest plantations, grassland, tea plantations, and waterbodies / wetlands. The bushland and crop fields is the dominant land cover in the East and notable the Northeast of the case study area. Dense and sparse forest is the dominant land cover in the Southeast. Forest plantations and grassland are dominant land cover types in the Northwest and the South east.

A stripe pattern of forest plantations, grassland and sparse forest is clearly visible in the Southwest of the map. This stripes are the result of missing data in the Landsat 7 SCL-off images that where included the monthly Landsat composites. While these stripes are visually evident, it is unlikely that they affect the accuracy of the map significantly. This applies notably for the biomass supply potential that will be aggregated to areas with a radius between 5 and 10 km.

Table 4 present the validation output of the land cover classification. The overall accuracy of 58%, which corresponds to the total proportion of correctly classified samples, is rather low. The result are more differentiated if we differentiate the proportion of correctly classified pixels per land use class (sensitivity). Tea plantations (t), waterbodies and wetlands (ww), and dense forest (fd) show an accuracy above 65%. Bushlands (b) and sparse forest (fl), in contrast, show an accuracy below 46 %. The confusion matrix shows that the confusion between these two latter classes is one of the main reasons for this low accuracy.

Table 4: Validation output of the land cover classification

```
Confusion Matrix and Statistics

          Reference
Prediction  b bu  c fd fl fp  g  t ww
        b  28  0  9  1 11  1  6  0  0
        bu  0 10  2  0  1  0  0  0  0
        c  14  5 50  1  7  2 18  1  4
        fd  1  0  0 36  3  3  0  1  1
        fl 16  0  8  7 28  7  2  0  3
        fp  4  0  5  8 11 48  3  0  5
        g   2  1  4  0  0  5 25  0  1
        t   0  0  3  1  0  0  0  5  0
        ww  0  0  3  1  0  0  0  0 35

Overall Statistics

               Accuracy : 0.5799
                 95% CI : (0.5331, 0.6256)
    No Information Rate : 0.1838
    P-Value [Acc > NIR] : < 2.2e-16

                  Kappa : 0.5127
 Mcnemar's Test P-Value : NA

Statistics by Class:
                     Class: b Class: bu Class: c Class: fd Class: fl Class: fp Class: g Class: t Class: ww
Sensitivity           0.43077   0.62500   0.5952   0.65455   0.45902    0.7273  0.46296  0.71429   0.71429
Specificity           0.92857   0.99320   0.8606   0.97761   0.89141    0.9079  0.96774  0.99111   0.99020
Pos Pred Value        0.50000   0.76923   0.4902   0.80000   0.39437    0.5714  0.65789  0.55556   0.89744
Neg Pred Value        0.90773   0.98649   0.9042   0.95388   0.91451    0.9517  0.93079  0.99554   0.96651
Prevalence            0.14223   0.03501   0.1838   0.12035   0.13348    0.1444  0.11816  0.01532   0.10722
Detection Rate        0.06127   0.02188   0.1094   0.07877   0.06127    0.1050  0.05470  0.01094   0.07659
Detection Prevalence  0.12254   0.02845   0.2232   0.09847   0.15536    0.1838  0.08315  0.01969   0.08534
Balanced Accuracy     0.67967   0.80910   0.7279   0.81608   0.67522    0.8176  0.71535  0.85270   0.85224
```

3.1.2 Supply sources

Figure 8 provides an overview of all potential biomass supply areas. We considered crop fields and forest plantations as potential supply areas excluding privately or state owned large-scale forest plantations and protected areas (exclusion areas). Biomass supply from crop field is dominant in the East and notably in the Makambako Township Authority district and Wanging’ombe district. Forest plantations are dominant in the Northeast of the case study areas and in the Njombe district in the South of the case study area. The Northwest and Southeast of the case study area, in contrast, show little potential to supply biomass.

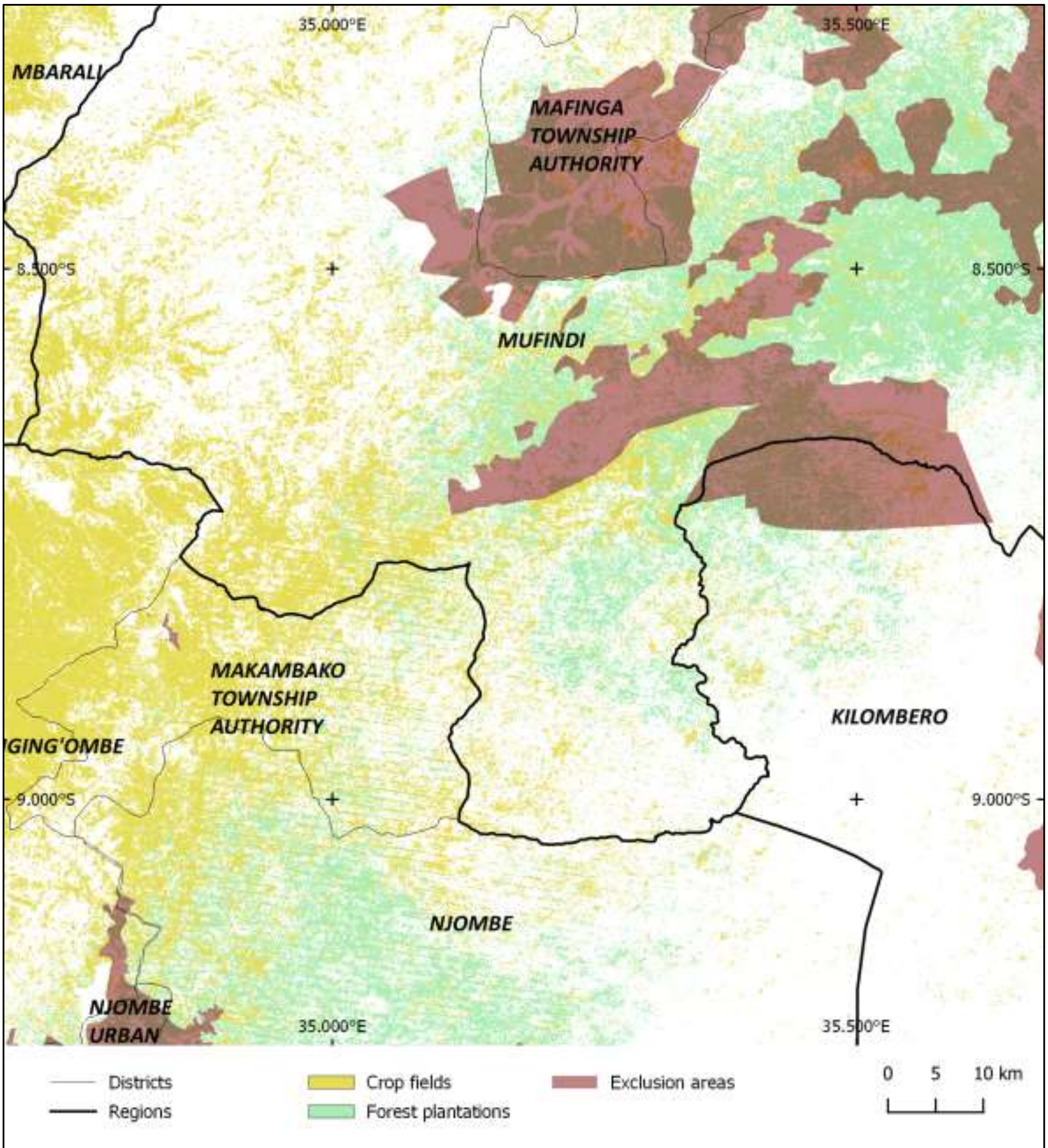

Figure 8: Biomass supply areas (crop fields and forest plantations)

The validation results of the three aggregated land cover classes that are needed to identify the biomass supply areas (i.e. crop fields, forest plantations, and other) are substantially better than the validation results of all land cover classes. See Table 5 for the corresponding validation output. The overall accuracy is 70% with the following proportion of correctly classified pixels per land use class (sensitivity): 60% for crop fields, 72% for forest plantations, and 73% for all other land use classes (other). Notably crops show a considerably lower positive prediction value (number of correct prediction relative to the total number of times a class was predicted) implying that crop field might be over predicted. Furthermore, the identified forest plantation areas seem to correspond fairly well with the results of another forest plantation mapping project (Mankinen et al. 2017) in that area (cf. Appendix 6.3).

Table 5: Validation output of the biomass supply areas only

```
Confusion Matrix and Statistics

                    reference
prediction            crops forest plantations other
  crops                  50                  2    50
  forest plantations      5                 48    31
  other                  29                 16   226

Overall Statistics

               Accuracy : 0.709
                 95% CI : (0.665, 0.7502)
    No Information Rate : 0.6718
    P-Value [Acc > NIR] : 0.049035

                  Kappa : 0.4551
 Mcnemar's Test P-Value : 0.008663

Statistics by Class:
                     Class: crops Class: forest plantations Class: other
Sensitivity                0.5952                    0.7273       0.7362
Specificity                0.8606                    0.9079       0.7000
Pos Pred Value             0.4902                    0.5714       0.8339
Neg Pred Value             0.9042                    0.9517       0.5645
Prevalence                 0.1838                    0.1444       0.6718
Detection Rate             0.1094                    0.1050       0.4945
Detection Prevalence       0.2232                    0.1838       0.5930
Balanced Accuracy          0.7279                    0.8176       0.7181
```

3.2 Biomass estimation

3.2.1 Productivity

Table 6 shows the values for the collected biomass aggregated from the subplots to the plot. The first column indicates the land classes of the field collection plot, the second column presents a description of the collected biomass, the third column indicates additional relevant information about the context (field collection, availability of the biomass, etc.) and the last column presents the estimated biomass supply potential per year and square meter given in kg of dry weight (brown MC approach).

This field data results in an average of 0.2 kg (SD: 0.097) dry weight biomass per square meter in crop fields and 0.46 kg (SD: 0.086) dry weight biomass per square meter in forest plantations. The total potential for biomass feedstock with the case study areas accounts for approximately 167,000 tonnes; 48,000 tonnes form crop fields and 119,000 tonnes from forest plantations.

Table 6: Biomass field collection per plot type

Plot_type	Biomass_type	Notes	Dry weight (Kg per year and m2)
Cropland	Maize stalks and leaves (70%), grasses and shrubs (30%)	Test data from 30 m plot split into 15*15 m quadrants	0.311
Cropland	Maize stalks and leaves (70%), grasses and shrubs (30%)	Neighbouring plot to test plot (P1) for comparison	0.293
Cropland	Peas stalks and pods	Large field, already cleared in piles	0.141
Cropland	Peas stalks and pods	Large field, already cleared in piles	0.103
Cropland	Maize stalks and leaves (80%), grasses, shrubs and ferns (20%)	Large field, already cleared in piles	0.245
Cropland	Maize stalks and leaves (95%), shrubs (5%)	Village garden, planted each year with maize, no crop rotation	0.094
Forestry	Pine needle ground litter, 4 years old, 2 years deposition	For annual availability, divide by 2 years (age of plantation minus first 2 yrs of young	0.367

		growth), as young trees produce very little and compensate lat~	
Forestry	Pine needle ground litter, 7 years old, 2 years deposition	Pruned branches and litter collected on the same plot but weighed separately	0.568
Forestry	Pruned branches, 3rd y pruning	Use as firewood second choice and limited to plantations surrounding villages, majority left in plot, or cleared and burned for fire prevention	0.476
Forestry	Pruned branches, 4th year	Pruned branches and litter collected on the same plot but weighed separately	0.423

3.2.2 Magunguli supply catchment

The experience in the field showed that in practice biomass is being collected within a 5 km distance from the production facility is reasonable (with a maximal distance of 10 km). Typically, producers rent a tractor and trailer for a fixed price and try to conduct one trip in the morning and one trip in the afternoon. Figure 9 shows the biomass supply areas within different radii between 5 and 10 km.

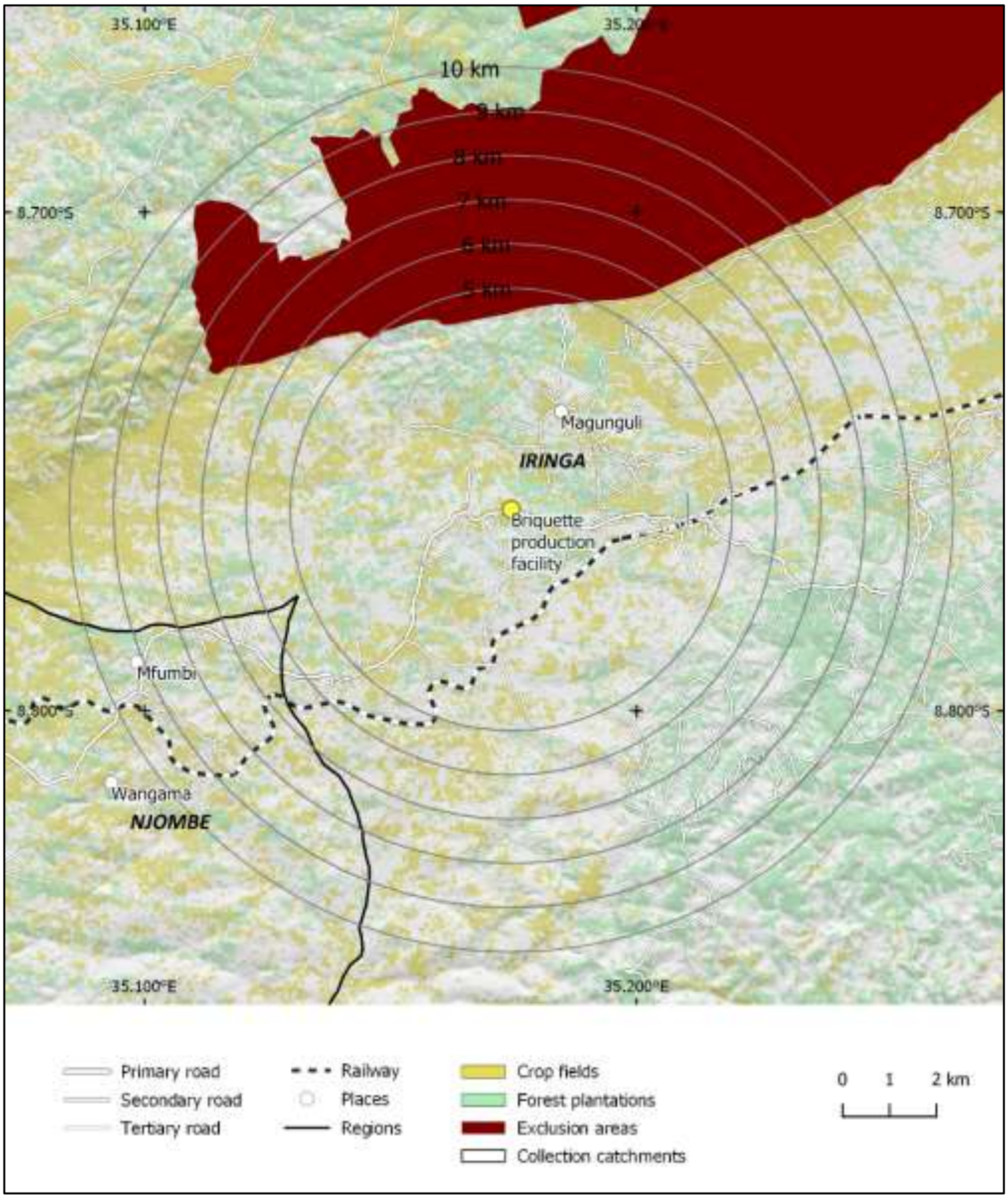

Figure 9: Biomass supply areas (crop fields and forest plantations) within different collection radii around the briquette production facility

Figure 10 provides the total biomass supply potential for each biomass supply areas (i.e. radii between 5 and 10 km). Assuming a biomass supply area with a radius 5 km yields in a potential biomass supply of 1,240 tonnes per year (dry weight); assuming a radius of 10 km would yield in a potential biomass supply of 4,590 tonnes per year (dry weight).

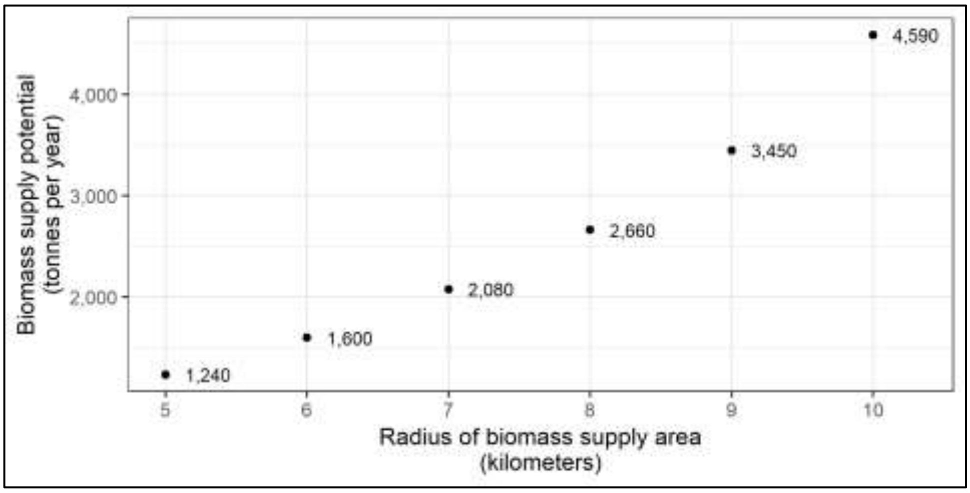

Figure 10: Biomass supply potential for the Magunguli production site assuming different collection radii

The circular area around briquette production facility is certainly a simplified assumption for the potential biomass collection catchment. In theory and practice, the area is limited by a maximal distance or travel time distance between origin of the biomass, the site of pyrolysis and the production facility (or a larger transport network to the facility). This encompasses the maximal spatial distance or travel time a char dust supplier is willing to travel between the area of biomass pyrolysis and the production facility, based on transport cost, accessibility, road network, season, and many other factors that are not considered here. Therefore, it is likely that not all biomass in these supply areas would be accessed for the collection of biomass. Hence, the biomass supply numbers might be overestimating the actual supply potential. At the same time, transport was observed in the field under extremely inaccessible circumstances, such as transporting several bags of recently pyrolysed char dust on the back of a motorcycle along walking paths between agricultural fields. In any case, we believe 5 km from a production facility or maintained road represents a viable upper limit for biomass collection and pyrolysis.

3.3 Scenarios of upscaling production across the landscape

3.3.1 Supply potential map

Figure 11 show the biomass collection potential assuming a collection radius of 5 km, i.e. each pixel show the total supply potential within an area of 5 km around that respective pixel. High supply potentials can be found in the centre of the case study area, north and south the briquette production facility, in the Northeast of the case study area, and in the South in Njombe district. The areas in the Northwest, Southwest and Mafinga Township Authority district show only low supply potentials.

3.3.2 Potential facility sites and biomass harvest areas for the upscaling scenario

Based on the production cost models developed for the upscaling scenarios (Appendix 0), both small-scale production scenarios (“observed” and “optimized”) were not economically profitable with briquette sales alone at the market price (TSH 500 per kg). The upscaled scenarios both showed profitability, largely due to the increase in productivity of the briquette machine to 2 tonnes biomass per day. Total biomass use per year for both upscaled scenarios was ca. 2’000 tonnes. However, sensitivity analysis showed that profitability could be achieved at production levels of 800-1’000 tonnes per year, depending on other model assumptions. Thus we set a lower limit on available biomass within 5 km for siting briquette production facilities of 1’000 tonnes per year.

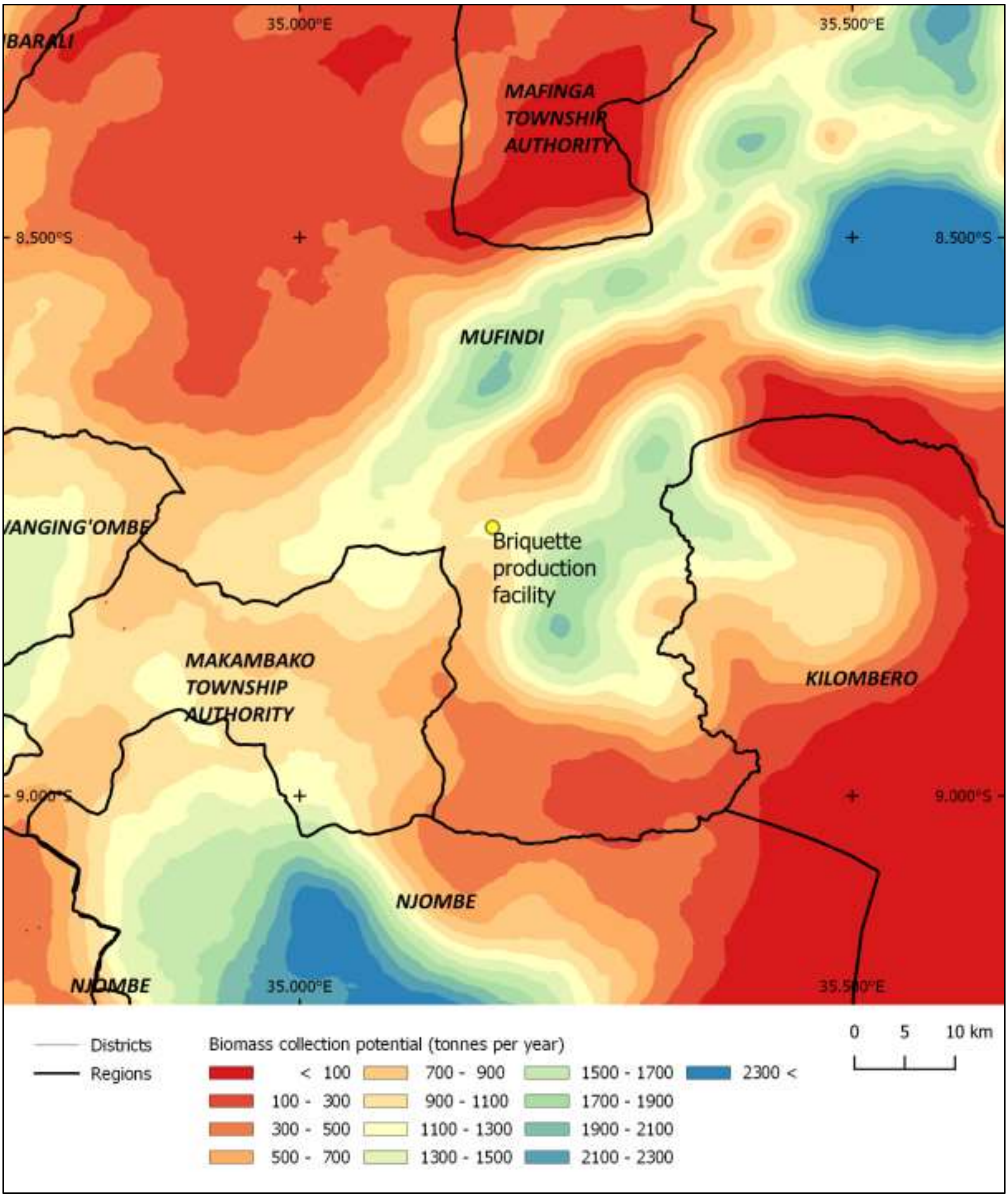

Figure 11: Biomass collection potential assuming a collection radius of 5 km

Based on applying this threshold, a set of 20 potential production sites was chosen and placed in the landscape based on consultation with local partners regarding site access, transportation potential and biomass availability. These potential facility sites are shown in Figure 12.

In a second step, for the "centralized" scenarios, we assumed that char dust could be collected along all trunk, primary, secondary and tertiary roads in the case study region. We thus assumed the potentially all biomass within 5 km of one of these roads could be collected. This biomass harvest buffer is also shown in Figure 12.

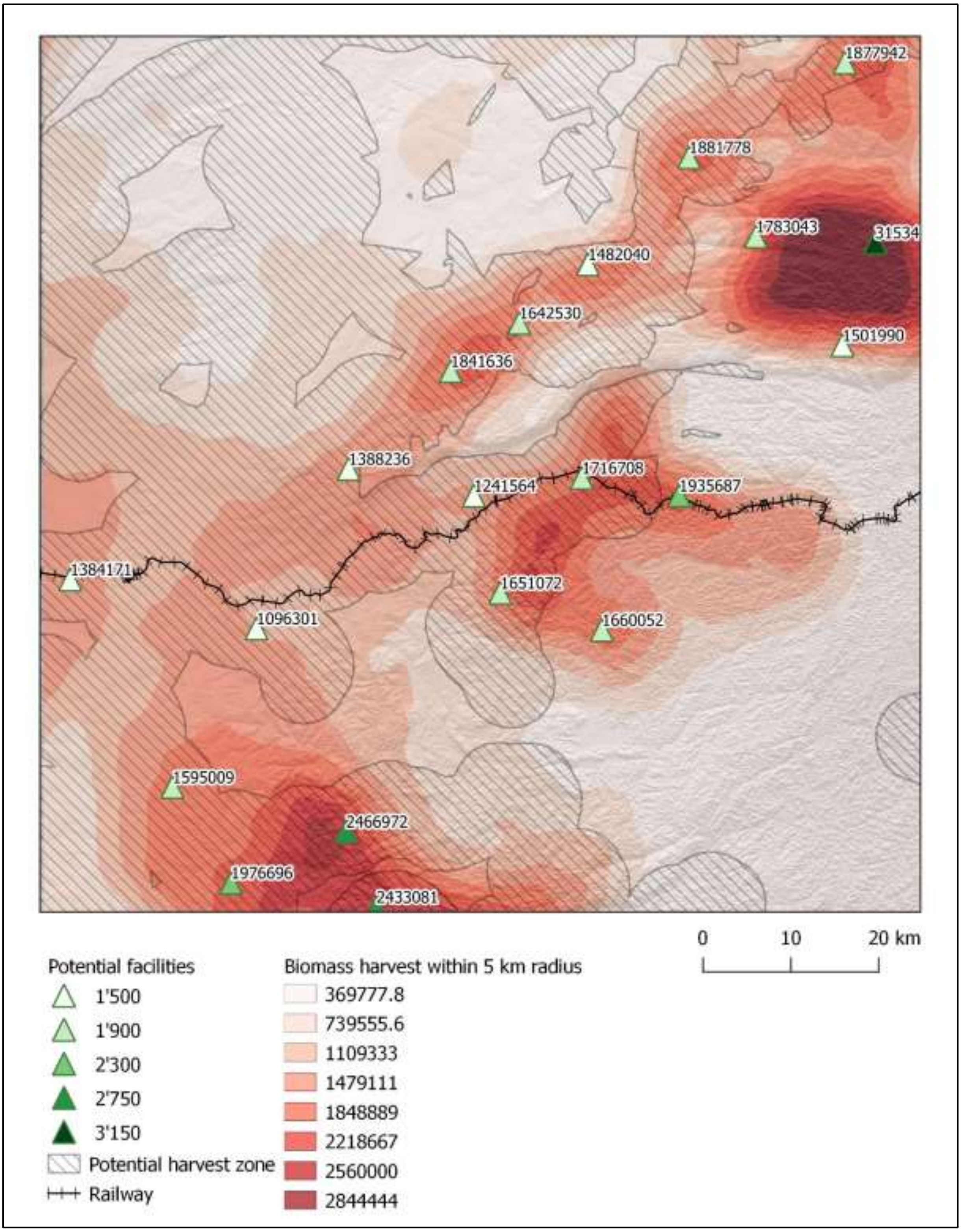

Figure 12: Potential briquette facility sites with at least 1'000 tonnes of biomass within a maximal collection radius of 5km (actual biomass availability shown above each symbol). For the "centralized" scenario, a harvest buffer of 5 km is shown around all (up to tertiary) roads (hatched polygon).

3.4 Impact assessment of upscaling

3.4.1 Production and job creation

Based on the upscaling scenarios developed (see above and section 2.5), we estimated the total production of briquettes based on the available biomass. Using information from our business models of each facility (Appendix 0), we could predict the total number of regional jobs that would be created (split into rural and urban jobs). These statistics are shown in Table 7. In all scenarios, we could achieve the reference agricultural salary of TSH 10’000 per day. In the case of centralized scenario, transport costs for char dust was much lower than for finished briquettes because of ease of handling. Thus a wage of TSH 15’000 was possible (which is generally appropriate to the urban production setting of the centralized scenario).

Table 7. Production statistics, employment of upscaling scenarios

Scenario	**Biomass harvest (t)**	**Char dust production (t)**	**Briquette production (t)**	**Total employment (FTE)**	**Rural jobs (%)**	**Urban jobs (%)**
Decentralized	35'710	8'927	8'182	239	100%	0%
Centralized 25%	22'694	5'674	5'200	152	71%	29%
Centralized 50%	45'389	11'347	10'400	303	71%	29%
Centralized 75%	68'083	17'021	15'600	455	71%	29%
Centralized 100%	90'778	22'694	20'800	607	71%	29%
Combination 65%	59'005	14'751	13'520	394	89%	11%
Combination 100%	81'700	20'425	18'720	546	79%	21%

3.4.2 Meeting charcoal demand

In total, our scenarios resulted in an estimated 8’000 – 20’000 tonnes of briquettes being produced per year. This figure is based on pyrolysis conversion efficiency of 25% (i.e. dry weight in to dry weight out). This is the lower estimate from field trails of pyrolysis with the “flame curtain” method (see Appendix 6.5). Putting this in context to potential demand in the three main urban markets (Njombe, Mafinga and Makambako) shows that the regional production of briquettes could meet between 14% and 55% of regional charcoal demand

Table 8. Charcoal consumption estimated in the urban markets. Consumption data from Mwampamba (2007)

Charcoal markets	**Makambako**	**Mafinga**	**Njombe**	**Total**
Population (ca. 2012)	93'800	51'900	130200	275'900
National average urban charcoal consumption (kg)	138	138	138	138
Total consumption (t)	12'944	7'162	17'968	38'074

3.4.3 Avoided environmental impacts

To gauge the degree of environmental benefits that could emerge from a substitution of conventional charcoal with waste-based charcoal briquettes, we took estimates of deforestation caused by charcoal production from the literature (Mwampamba 2007; Felix and Gheewala 2011). We combined this with estimates of carbon density in Tanzanian forest (Harris et al. 2012). The results suggest that the average scenario of regional upscaling of briquettes production could substitute for 13’203 tonnes of conventional charcoal (Table 9). Assuming charcoal production is the main driver of land use change in the region, this translates to a potential avoided forest loss of 4’251 ha. Substituting for conventional charcoal could thus potential prevent the emission of over 208 thousand tonnes of carbon caused by forest degradation and conversion. In comparison to national emissions levels (in the year 2014), this amounts to a reduction of almost 0.1 percent. This is a sizeable contribution given that our model only covers a small region in Tanzania. Upscaled to the entire country, where suitable waste-biomass exists and would otherwise be burned, the overall contribution to climate change mitigation could be very substantial.

Table 9. Potential for avoided deforestation and carbon emissions of charcoal briquettes (assuming full substitution of conventional charcoal)

Char briquette potential environmental impacts	**Production (t)**	**Source**
Average scenario production	13'203	This study
National forest loss due to charcoal, middle estimate (ha y-1), ca. 2002	241'500	Mwampamba et al. (2007)
National charcoal consumption (t), ca. 2000	750'000	Felix and Gheewala (2011)
Forest loss per unit charcoal consumption (ha y-1/t)	0.322	
Average avoided forest loss (ha y-1)	4'251	
Carbon density of forest (t C ha-1)	49	Harris et al. 2012
Avoided carbon emissions (t C y-1)	**208'318**	
National emissions in 2014 (t C y-1)	286'490'000	www.climatelinks.org
Potential contribution to national emissions reductions	**0.073%**	

4 Discussion and conclusion

The report presented above illustrates the importance of efficient use of available biomass in Tanzania. As a country with a strong dependence on biomass energy (Felix and Gheewala 2011; Zah and Ehrensperger 2014), it is crucial to consider all sources of biomass and their uses when building a coherent policy to meet demand. In this study, we turned our attention to optimizing biomass use in a rural case study in the Southern Highlands, where harvest waste from is crops is typically gathered in piles and burned. We illustrated that such waste biomass within a single region has the potential to meet a significant portion (ca. a third) of urban demand for charcoal in nearby market centres.

Income generation

In terms of socio-economic impacts, this would create hundreds of full time job equivalents in rural areas, depending on the scenario. However, the main benefit would not take the form of full time jobs, but rather additional income for farmers with little additional work in addition to regular field clearing activities. Through the pyrolysis rather than burning of crop residues, such income would be distributed across a much wider range of beneficiaries. The additional work required for each farmer was estimated during three pyrolysis trails with the “flame curtain” method of char dust production (Cornelissen et al. 2016; Pandit et al. 2017), in addition to much practical experience on the part of the project partners. In general, about 3-4 hours of additional labour is required for pyrolysis of biomass of ca. 2000 m2 of land. The average plot size for farmers in Tanzania[2] is ca. 2.5 ha, implying 12.5 pyrolysis event with an assumed 2 harvests per year and half the crops being suitable for pyrolysis. Expressing the full time equivalent of job creation in terms of pyrolysis events for the average farmer, we come to a total number of beneficiaries of upscaling the scheme to between 33’280 and 133’119 individual farmers (Table 10).

Table 10. Estimated number of beneficiaries, defined as farmers earning additional income from char dust production (assuming 2 harvests, biomass requirements for pyrolysis event of 0.2 ha and additional time requirement of 4 hours)

Scenario	Pyrolysis events (#)	Average farm size (ha)	Pyrolysis events per farmer (#)	Beneficiaries (#)	Additional income per beneficiary (TSH)
Decentralized	916408	2.5	12.5	73313	187’500
Centralized 25%	415997	2.5	12.5	33280	187’500
Centralized 50%	831993	2.5	12.5	66559	187’500
Centralized 75%	1247990	2.5	12.5	99839	187’500
Centralized 100%	1663987	2.5	12.5	133119	187’500
Combination 65%	1343422	2.5	12.5	107474	187’500
Combination 100%	1663987	2.5	12.5	133119	187’500

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[2] http://blogs.worldbank.org/africacan/land-of-opportunity-should-tanzania-encourage-more-large-scale-farming

A single pyrolysis event delivers about 3 units of char dust, which we assume in our economic model to be purchased for TSH 5’000. This price was negotiated in the field during the pilot project and represents a strong incentive for char dust production. Thus, a single pyrolysis event would deliver ca. TSH 15’000 of additional income, which is about 1.5 times the daily average wage in agriculture for half a day’s additional work. Thus, farmers could generate almost 20 days’ worth of additional income each year. For a full time equivalent of 240 days per year, that equates to an income rise of ca. 8% for an additional 6.25 days of work per year (ca. 2.6% increase). Thus the benefits for rural char dust producers would greatly outweigh the additional time requirements and deliver a strong net income increase.

For Briquette producers, the income achieved for the full time jobs at least matches or exceeds the reference salary for agricultural work. In the scenarios of decentralized production, wages were set at a lower rate (TSH 10’000 per day) due to higher costs elsewhere (mainly packaging, transport and water/energy facilities). In the centralized scenarios, reduce costs could facilitate higher wages (TSH 15’000 per day). Both of these figures are roughly in parity with reference rural and urban wages, respectively. Thus, no major income increase is expected beyond the basic benefit of job creation.

Forest conservation

Regarding environmental benefit, the study showed that substitution of conventional charcoal with char briquettes could have a considerable impact on forest loss due to charcoal production. Here, we assume that charcoal production is a direct driver of forest loss in the case study region. Our estimates of forest loss per unit of charcoal are taken from the literature (Mwampamba 2007). Yet charcoal production on private land may be a bi-product of land use change that would otherwise occur (e.g. clearing for agriculture or forestry by new settlers or existing land owners with additional capacity to bring land under the plough). In such a case, the charcoal represents an additional income generating activity next to the primary aim of land clearing, but it would be produced regardless of external demand. Substitution of briquettes for such charcoal would not deliver the promised benefits of reducing land clearing unless the oversupply to the market reduced prices and incentives to professional charcoal producers elsewhere. At the same time, a reduced price could stimulate demand which would then offset even this partial benefit.

In the Southern Highlands, a Private Forestry Programme (PFP), or “Panda Miti Kibiashara” has been running for several years, funded as a bilateral programme of the Tanzanian and Finnish government[3]. This programme aims at “increasing rural income in the Southern Highlands area of Tanzania through developing sustainable plantation forestry and value addition“[4] through capacity building and financial support. While environmental criteria are present within the project goals (e.g. in establishing conservation zones for biodiversity), the net results is facilitating the conversion of native woodland on private lands into exotic forestry plantations. Personal accounts by locals in the area confirmed the expansion of exotic forest plantations (mainly pine) in the area over the past couple of decades (alongside conversion to agriculture). This is supported by a recent mapping study by the PFP programme, which found a majority area of young-stage forestry stands established on private lands in contrast to mature-stage stands in public and commercial plantations (Mankinen et al. 2017). This implies forestry expansion is a major driver of land use change in the area. If charcoal from native woodland is assumed to be a bi-product of this expansion, and not an end in itself, then char dust briquettes will have little impact on land clearing until other incentives, such as those of

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[3] http://www.privateforestry.or.tz/en/about/partnerships

[4] http://www.privateforestry.or.tz/en/about/category/who-we-are

the PFP, are addressed. Therefore our environmental results must be interpreted with extreme caution, particularly in the context of the Southern Highlands.

That said, given the massive demand for charcoal across the country, the net result of introducing char dust briquettes is likely to be positive. Even if half of the potential benefits that we estimate are realized, promoting this technology would still deliver a substantial reduction in charcoal-related carbon emissions due to land use change. A clear next step would be to assess the drivers of land use change in different parts of the country, along with the structure of the charcoal market, and strategically introduce char briquettes where the context is correct. This means areas where agricultural wastes is burned rather than used for another means (e.g. compost, animal feed), where deforestation is largely driven by charcoal demand and where marketing of briquettes matches the target markets for such charcoal.

In conclusion, the production of char dust briquettes represents an attractive option for increasing the efficiency of biomass use whilst simultaneously raising incomes and providing rural jobs. Our results support this optimism under simplified assumptions, particularly in the social domain. At the same time, the introduction of the technology is not a panacea for environmental problems associated to charcoal, because their causes are generally more complex than first appears. Thus char dust briquettes from agricultural waste must be considered one possible intervention that needs to be coordinated with other changes in incentives and environmental management practices across the agricultural and forestry sector.

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