Working Paper:

Carbon storage in Jatropha curcas trees in Northern Tanzania

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Abstract

This study investigates the carbon sequestration capacity of *Jatropha* curcas, a tropical tree-like shrub that is widely cultivated for the production of oilseeds for biodiesel and biokerosene. It applies a destructive research approach on fifteen Jatropha trees of different ages growing in the field in semi-arid tropical conditions in Northern Tanzania. It estimates allometric equations for the relationship between basal stem diameter and above-ground dry biomass, and total dry biomass, respectively. It also measures the carbon content in a range of dry wood samples with a carbon analyzer. The results can be useful for estimating carbon sequestration capacity of *Jatropha* curcas biofuel projects in semi-arid conditions for the purpose of obtaining carbon finance, and for assessing the contribution of carbon sequestration in Jatropha biomass in the context of biofuel life-cycle analyses.

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1. Introduction

Since the ratification of the Kyoto Protocol, carbon trading between parties in developed countries (the “Annex I countries”) and developing countries has rapidly turned into a popular financing instrument for a variety of greenhouse gas emission-reducing projects in the latter. In carbon trading, what is being traded is a certificate that guarantees a certain carbon-dioxide emission reduction or a certain amount of avoided emissions as a result of the implementation of projects in fields like renewable energy generation and enhancement of energy efficiency in energy-intensive plants. Reforestation, afforestation and ecosystem protection activities which were originally not part of the Kyoto Protocol are now also being brought into the fold of international carbon finance under the REDD and REDD+ mechanisms.

In the case of reforestation or afforestation projects, in which carbon is sequestered in trees, the total amount of carbon credits produced is determined by the average amount of carbon stored in the trees. It is therefore essential to have good information about the extent of carbon that can be sequestered in the trees of such projects. Large projects aiming at (re)forestation or native forest protection tend to rely on GIS methodologies and aggregated biomass and carbon estimates per ha for particular forest ecosystems, but such aggregated methodologies are not suitable for projects designed around single tree species, as is common in tree-based biofuel projects. This study investigates the carbon sequestration capacity of *Jatropha* curcas, a tropical tree-like shrub that is often cultivated for the production of oilseeds for biodiesel and biokerosene. So far, the carbon sequestration function of Jatropha trees has received much less attention than its oilseed production potential, but there is a growing interest in exploiting its potential carbon sequestration services. Moreover, the carbon sequestration capacity of Jatropha shrubs is an essential determinant of the overall greenhouse gas reduction performance of its biofuel (Bailis and McCarthy, 2011).

Two aspects are specifically important for reliable carbon sequestration estimations in single species systems like Jatropha. First, one needs to determine the (dry) biomass content of a set of representative trees, growing under the ecological circumstances prevailing in the project area. Second, one needs to find out how much of this biomass actually constitutes carbon. The question how much dry biomass is accumulated in a *Jatropha* curcas tree was first addressed by Henning (see Benge, 2006), Reinhardt et al. (2008), Francis et al. (2005) and Struijs (2008). However, these early publications were based on rough estimations or unverifiable sources and unclear methods. Destructive research, in which the weight of a *Jatropha* tree is determined by digging out and actually weighing the tree, would give a more accurate idea of the biomass that is produced in a *Jatropha* tree.

To our knowledge, only a few recent studies have applied a destructive research approach to *Jatropha* trees so far, but these studies still have various limitations. Ghezehei et al. (2009) researched the above-ground biomass of 12 randomly sampled, and destructively tested trees from three different height categories, with ages varying from 16 to 26 months in South Africa, where the trees grew at a university research plot. However, the below-ground biomass was not examined in his research. Destructive research carried out by Bailis and McCarthy on five trees in Brazil and six trees in India, aged between two and four years, has the same limitation (2011). Firdaus et al. (2010) selected three trees of 10, 17 and 32 months, respectively, that were grown at a university plot in Malaysia for destructive testing. They did determine both their above- and below-ground weights. This study thus had a better methodology than the other two studies, but the number of trees was very limited, and the sample did not include any mature specimen. Achten et al. (2010) identified the biomass production of young seedlings over time in a controlled greenhouse setting, under different drought conditions. They measured the seedlings on a regular basis, till they reached an age of 116 days. Furthermore they validated the results from their greenhouse experiment with three three-years old trees and three 12 years ones from a university plot in India. Their stem and branch diameters were taken, and the above-ground weight was determined. However the validation did not yield good results. Most likely the very young age of the greenhouse sample was insufficient to predict the biomass in more mature trees.

The second issue, the fraction of carbon that is present in the tree biomass, has attracted only minimal attention so far. Only Firdaus et al. (2010) conducted actual measurements on Jatropha wood samples to determine the carbon fraction with a carbon analyzer. All the other studies applied a common rule of thumb that approximately 50% of the dry biomass constitutes carbon.

This study aims to contribute to the knowledge regarding the biomass production of *Jatropha curcas* by applying a destructive research approach on *Jatropha* trees of different ages in the field in semi arid tropical conditions. This setting constitutes an environment that is commonly mentioned as a suitable location for the cultivation of Jatropha biofuels. A total of 15 trees were sampled, with varying growing conditions, and ages varying from 2.5 to 25 years old. Data from these trees were used to give an idea about the dry biomass that a *Jatropha* tree produces, and to develop allometric equations. Compared to the existing publications described above, this study includes several more mature trees that were grown in realistic field conditions, researches both above- and below-ground biomass, produces site-specific data for northern Tanzania, tests the allometric equations from the earlier literature in the Tanzanian situation, and develops new allometric equations for that situation. Furthermore, tree-samples were further analyzed to identify the actual carbon fraction of *Jatropha* biomass, both to compare with the results of Firdaus et al. (2010), and to search for variations in carbon fraction in different circumstances, as well as variations in different parts of the trees. To the best of our knowledge this study is the first attempt to research all physiological aspects of *Jatropha* curcas that are relevant for the development of a carbon finance project and/or for estimating carbon sequestration in Jatropha biomass as part of a greenhouse gas life-cycle analysis of Jatropha biofuel, together in one study.

2. Literature review

This section summasizes the most salient findings from the extant research regarding the biomass production and carbon content of *Jatropha* curcas.

The main objective of the research done by Ghezehei et al. (2009) was to examine the reliability of a tree's basal diameter and crown-depth, in predicting above-ground variables, such as biomass weight. These relationships were also tested using independent data. They identified three height categories from trees with ages varying from 16 to 24 months old. These categories were: shorter than 1.2 m, between 1.2 m and 2 m, and taller than 2 m. From each category four trees were sampled randomly from a plot at the Ukulinga research farm at the University of Kwazulu Natal, in South Africa. This study site was situated at an elevation of 781 m above sea level, and was described as a site with hot and warm summers, mild winters, and an annual rainfall of 680mm. The trees were cut off at ground level, all relevant variables were measured just before cutting. Then samples were taken from leaves, branches and stem. These samples were oven dried at 73°C, and then weighed with an electronic balance to determine the dry weights. Highly significant relationships were found between the above ground variables and the basal stem diameter and the crown depth, respectively. The basal stem diameter is generally preferred since this is easier to measure. The allometric equations for the relationship between the basal diameter (BD) and the total above-ground dry mass (TAM), and with the woody above-ground dry mass (WAM), are as follows (weights in grammes, diameters in millimetres):

$$TAM = 0.000907 BD^{3.354} \qquad (R^2 \geq 0.89) \qquad (1)$$

$$WAM = 0.000283 BD^{3.529} \qquad (R^2 \geq 0.94) \qquad (2)$$

The woody above-ground dry mass does not include the leaves, while the total does. The study also concluded that neither below-ground competition with other species nor tree spacing had significant effects on allometry. They did affect the growth and size of trees, but this is a proportional effect, resulting in constant allometric equations. The authors recommend the inclusion of data from additional study sites, to test the wider applicability of the equations.

The study by Achten et al. (2010) determined the biomass allocation and allometric relationships for young *Jatropha* seedlings, under three different levels of drought stress. The drought levels were simulated in a greenhouse at the K.U. Leuven University in Belgium. All non-destructive measurements, such as stem diameters, were collected at the ages of 64, 78, 92, and 116 days. After this last measurement the weights of both above- and below- ground parts were determined. Furthermore, dry masses were determined after oven-drying at 105°C until a constant weight was reached. The results from these measurements were used to calculate the root-shoot ratios (root biomass divided by aboveground biomass, with or without leaves). They indicate that water stressed seedlings had significantly higher root-shoot ratios compared to wet treatment plants, but they are all around 0.50 for these young seedlings, if the leaves are not included. The wood density they found is 0.26g/cm^3, and did not vary among the different treatments, this is similar with other reported densities of *Jatropha curcas*, also on older trees. The allometric equation that was developed from the seedlings is as follows (weights in grammes, diameters in millimetres):

$$TAM = 0.029BD^{2.328} \qquad (R^2 = 0.89) \qquad (3)$$

This equation gives a good estimation of the total above ground biomass of the seedlings. The allometric equation was then tested on more mature trees. From three trees of three years old, and three of 12 years old, the diameters at ground level were measured before they were cut. Then the total above-ground fresh and dry weights were determined. These trees grew at a plantation of the CCS Haryana Agricultural University in India. Neither the developed allometric relationship, nor a more general one from literature, predicted the above-ground weight with acceptable accuracy.

However, if applied to each first-order branch individually, a similar equation produced a good prediction. This equation is:

$$TAM = 0.03BD^{2.68} \qquad (R^2 = 0.92) \qquad (4)$$

The main objective of Firdaus et al. (2010) was to determine the potential of *Jatropha curcas* to sequester carbon. The study was executed at the agriculture park of the Putra University in Malaysia, where a total area of one hectare is planted with *Jatropha curcas*, at a planting distance of 2x3m. Three trees of different ages (10, 17, and 32 months) were researched. The trees were sawn down at the base of the stem, after which the fresh weight of the above-ground part was directly determined. Then the below-ground parts were excavated. All tree parts were subsampled and oven-dried till a constant weight was reached. Later the samples were ground to 2mm for total carbon content determination by means of a carbon analyzer. Furthermore, litterfall was collected from nine randomly selected trees, photosythesis was measured, and soil carbon was analyzed. The measurements on soil and litterfall did not indicate any addition to the total carbon content of soil by the litterfall. The results of this study are reproduced in Table 1. The carbon data in the table suggest that Jatropha's carbon fraction is well below the commonly assumed 0.5.

Table 1: Results of Jatropha dry weight and C-content measurements by Firdaus et al (2010) in Malaysia

Age [months]	C-content (above-ground)	Dry biomass without leaves (above-ground)	C-content (below-ground)	Dry biomass without leaves (below-ground)
32	46.9%	12.68 kg	46.9%	3.95 kg
17	46.8%	6.60 kg	46.8%	2.32 kg
10	46.2%	1.23 kg	44.6%	0.70 kg

Bailis and McCarthy (2011) sampled five trees of four years old (all pruned) from a 250 ha Jatropha plantation in Tamil Nadu, India. The area has a reported annual average rainfall of 812 mm and the black loamy soil is considered to be of low agricultural productivity. The six Brazilian trees were two year old (two pruned, four unpruned) from a 187 acres Jatropha plantation near Jaiba, Minas Gerais, on cambissols and latissols whose previous land use was mainly dry shrub/dry forest known as Caatinga woodlands. Stems, branches, leaves and fruits were separately dried at 70 degrees C for four days in order to obtain their dry biomass weights. The average biomass weight for the unpruned Brazilian trees came to 4.7 kg, the pruned Brazilian trees to 13.6 kg, and the Indian pruned trees to 13.6 kg. The authors observe that pruning encourages biomass formation. They use these figures to develop biomass estimates for larger Jatropha stands in the respective areas. They also give carbon estimates, based on an assumed 0.5 carbon fraction. Allometric equations for Jatropha were not developed.

3. Data collection and research approach

3.1 Sample trees and research location

For this research project, the first eight trees were excavated in June 2010. This was done at four different locations, in Arusha region, Northern Tanzania. In June 2011 another 7 trees were excavated at four other locations in Kilimanjaro and Singida regions, also in Northern Tanzania. The exact GPS locations of all trees were saved and are available on request.

The first four trees were excavated in the city of Arusha itself, they were taken from a hedge, and a small plot of trees at an industrial area. These trees were 2,5 years old, and irrigated on a regular basis. The first and second tree originate from seeds, the third and fourth are from cuttings. The first two trees were planted on a square plot, with planting distances of approximately 1.5x1.5 m. The third and fourth tree were planted in a hedge, with planting distances of approximately 1.2 meters. All four trees had an average size compared to the surrounding trees.

The fifth tree was excavated at a demo plot near the village of Selela. The environment in Selela is very dry, and the plot was located uphill, away from the river, on dry, sandy ground where nothing else grew at the time of visit. This tree was neither irrigated, nor fertilized, and originates from a seed. The planting distance was approximately 1.5x2m.

The sixth and seventh tree were excavated at a demo plot near the village of Engaruka Juu. This is in the same region as Selela, but closer to the river. At this plot some grass could be found in between the *Jatropha* trees at the time of visit. The trees were neither irrigated, nor fertilized, and originate from seeds. The trees were planted with distances varying from three to five meters. The sixth tree was among the larger trees, the seventh was among the smaller ones. They were 4 years old.

The eighth tree was also excavated in Engaruka Juu, from a hedge separating a farm from the (sand) road. It had been regularly irrigated, and fertilized on an irregular basis with cattle-manure from passing cattle on the road. According to the owner, the tree originates from a cutting, and was approximately 25 years old. Planting distance was approximately 1.2m.

Trees 9, 10 and 11 were excavated in the village of Kikuletwa. Trees 9 and 10 were planted in a hedge, tree 11 stood free. No irrigation or fertilization was applied. The ages of trees 9 and 10 are unknown, tree 11 is approximately 7 years old.

Tree 12 was excavated in the village of Uniyambwa. It is a three year old specimen planted from a cutting in a hedge and was neither irrigated nor fertilized.

Tree 13 was excavated in the village of Kisasida. It originates from a seed and was standing free. No fertilization or irrigation was applied. Tree 13 was 3 years old.

Trees 14 and 15 were excavated in the village of Sepuka. Tree 14 was planted in a hedge and originates from a cutting, tree 15 was standing free and originates from a seed. No fertilization or irrigation was applied. Both trees had an age of 3 years.

3.2 Measuring the trees

The same approach was followed in the case of all trees. They were excavated using spades, pickaxes and hands, while care was taken to not damage the root system, which stayed intact, except for tiny rootlets that remained in the ground. After excavation the number of first order branches, and the tree's above-ground height, below-ground height, and total height were measured. Also the trees' perimeters at ground level were measured using a flexible measuring tape. These were used to calculate the average diameters, this immediately corrects for the fact that the cross section may not be a perfect circle. Then loose sand and soil were removed from the roots, and all leaves were removed, before measuring the total weight of the tree as a whole (except for the ninth tree, which was too heavy to weigh in one piece). This weight was measured using a hanging scale with a maximum load of 100kg. Then the above- and below-ground parts were separated (using a pruning saw), and weighed individually with the same scale. Subsequently, from trees one through eight, three to seven subsamples were taken from different parts of each tree, leading to a total of 34 subsamples. The fresh weight of these subsamples was immediately measured using a Kern precision scale with a maximum load of 200 grams.

All subsamples were oven dried at 105°C, until a constant weight was reached. Immediately after drying, the dry weight of the samples was determined using the same precision scale. These measurements were used to calculate the dry weights of the trees. After drying, seven samples were ground using a steel file, to prepare for analysis with a CHN-analyser (Perkin Elmer 2400 series II). With this analyzer the exact weight fraction of carbon was measured. Seven subsamples from different trees, and different parts were measured, and every sample was measured twice. In between these measurements the samples were stored in a desiccator, to prevent the absorption of moisture by the samples.

3.3 Allometry

Allometric equations help to estimate characteristics of trees that are difficult to measure, making use of fixed relationships with characteristics that are easier to measure. Once a good allometric equation has been estimated, it can be used to predict the biomass of a tree without the need for destructive research. The diameter at ground or breast height is a commonly used predictor (e.g., Achten et al., 2010; Ghezehei et al., 2009). This study included destructive research for the purpose of empirically developing valid allometric equations for *Jatropha* curcas in northern Tanzania. Allometry is a site specific method: the same tree follows a different allometric relationship when exposed to different conditions (Pastor et al., 1984). The area from which the trees in this study were drawn can be characterised as semi-arid tropical. Large parts of Sub Saharan Africa have broadly similar ecological characteristics.

According to Pilli et al. (2006), the proportions between different parts of a tree maintain constant while the tree is growing. Therefore, a power function is generally used to predict a tree's biomass from the diameter. Such a function has the following form, which was also found in the publications by Ghezehei et al. (2009), and Achten et al. (2010):

$$Biomass = aD^b \tag{5}$$

One can choose which parts of the biomass one wants to estimate; this could be biomass with or without leaves, and could include or exclude below-ground parts. In this study leaves were never included, because only woody biomass has the potential to produce reliable carbon credits. The diameter can be taken at ground level, or at a certain fixed height above the ground. Since *Jatropha curcas* tends to develop its first-order branches very near to the ground, it is most convenient to use the diameter at ground (or base) level, as was also done in the studies by Ghezehei et al. (2009) and Achten et al. (2010). In this study, therefore, the relationship between the basal diameter and biomass is estimated. Separate equations are developed for the relationship with the above-ground dry woody biomass and the total dry woody biomass, which includes below-ground parts. Furthermore, trees that originate from seeds and from cuttings develop different root systems (FACT, 2011). This could have an influence on the below-ground proportion in the total biomass, with a constant basal diameter, and thus influence the allometric equation. Therefore the possibility to develop separate equations for the total biomass from seeds and cuttings is explored.

Growing conditions (e.g. irrigation or fertilization) should influence the tree's size and weight, but there is no reason to assume that it would influence the relationship between the variables in the allometric equation. Therefore all sample trees are used in the development of the allometric equations, despite the somewhat varying circumstances in which they grew. Furthermore, the intention of this study is to produce reasonably widely applicable equations to give general indications about the performance of *Jatropha* curcas in semi arid tropical conditions, rather than precise site-specific equations. An aspect that could have an important effect on the relationship between diameter and biomass is the pruning regime. One could imagine an old tree with a large basal diameter which is intensively pruned and has been reduced to, for example, only the single stem. In that case the above-ground biomass is heavily reduced while the basal diameter is still large. In this study, the sampled trees are selected as having an average shape for trees in the field that are also used for biofuel production. This means that the trees are kept in a shape such that the oilseeds will be relatively easy to harvest by hand, produce high fruit yield, and will not produce substantial shade for nearby foodcrops. This assumption is made because the aim of most projects is to combine carbon credits with biofuel production.

The allometric equations are estimated by means of a regression in SPSS. The significance and validity of the equations are evaluated with the R^2 value, the F-statistic, and a scatterplot of the residuals. Microsoft Excel was used to visualize graphs of the equations.

4. Results and analysis

4.1 Tree characteristics

The measurements from the sampled trees are summarized in Table 2. For the dry weight fraction an average value was calculated in order to reduce the impact of measurement errors. This average value was used in further calculations.

Table 2: Jatropha tree measurements, Tanzania sample

Tree ID	Age [years]	Diameter at base [cm]	Woody fresh weight [kg]	Dry weight fraction	Dry weight* [kg]	Above-ground weight [kg]	Below-ground weight [kg]	Root/shoot ratio	Origin	Seed or Cutting	Irrigated
1	2.5	16.1	33.7	0.23	7.62	26.2	7.5	0.29	Arusha	Seed	Yes
2	2.5	15.9	45.4	0.20	10.27	34.8	10.6	0.30	Arusha	Seed	Yes
3	2.5	13.1	29.5	0.23	6.67	24.0	5.5	0.23	Arusha	Cutting	Yes
4	2.5	12.7	23.2	0.24	5.25	18.6	4.6	0.25	Arusha	Cutting	Yes
5	2.5	6.5	2.8	0.21	0.63	1.7	1.1	0.65	Selela	Seed	No
6	4.0	11.1	13.5	0.24	3.05	10.0	3.5	0.35	Engaruka	Seed	No
7	4.0	8.0	6.3	0.22	1.43	4.9	1.4	0.29	Engaruka	Seed	No
8	25.0	43.3	137.3	0.24	31.06	95.5	41.8	0.44	Engaruka	Cutting	Yes
9	N/A	6.0	1.8	N/A	0.41	1.2	0.6	0.50	Kikuletwa	N/A	No
10	N/A	8.1	7.0	N/A	1.58	4.9	2.1	0.43	Kikuletwa	N/A	No
11	7.0	14.2	66.5	N/A	15.05	49.0	17.5	0.36	Kikuletwa	N/A	No
12	3.0	8.4	28.5	N/A	6.45	18.0	9.5	0.53	Unyambwa	Cutting	No
13	3.0	9.5	6.0	N/A	1.36	4.5	1.5	0.33	Kisasida	Seed	No
14	3.0	4.1	1.3	N/A	0.29	0.8	0.5	0.63	Sepuka	Cutting	No
15	3.0	10.0	11.5	N/A	2.60	8.0	3.5	0.44	Sepuka	Seed	No
Average values:				0.23				0.40			

* The same average dry weight fraction was used for all trees.
Source: fieldwork conducted by B.F. Hellings and S. Heijnen, Eindhoven University of Technology.

4.2 Carbon measurements

All ground wood samples were analyzed twice, to make sure the measurements were valid. The average of these two measurements is considered as the final result, they lie between 42.20% and 45.48 % carbon in the tree's woody dry weight (Table 3). All samples were ground from complete cross sections of the stem, branches, or roots, except sample 9c, which came from the centre part of the stem of a big tree.

Table 3: Jatropha C-content measurements, Tanzania sample

Sample ID	Above-ground (AG) or below-ground (BG) sample	C-content [% of total dry weight]
1	BG	42.20
2	AG	45.35
5	BG	42.71
6	AG	42.76
8a	AG	45.48
8b	BG	42.54
8c*	AG	42.81
Average:		43.41

* Sample 8c originates from the centre part of the stem, the others are full cross sections.

4.3 Allometry

The results in Table 2 were used to develop allometric relationships for the total woody dry biomass and for the above-ground woody dry biomass. All except three number eight were used in the regression. Tree eight was removed from the regression as an outlier, on the basis of the fact that its actual mass (total and above-ground, respectively) was more than three standard deviations away from the value predicted by the allometric equation. Due to its advanced age, its history - e.g. with respect to pruning - is relatively uncertain compared to the other trees. This might explain (in part) why this tree yields outlying values.

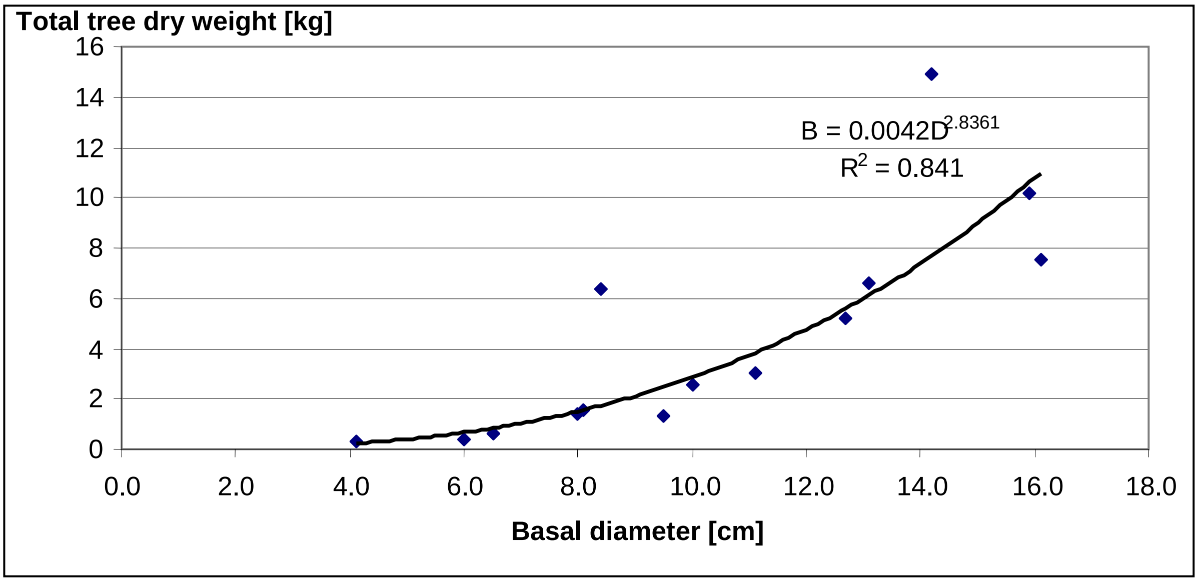
The average dry weight fraction was used in the dry weight calculations, rather than the individual fraction for each tree. Tests with different regressions showed slightly more significant results with the average overall value than with the individual fractions.

The first equation represents the estimated relationship between the basal diameter and the total (i.e., above- and below-ground) woody dry biomass:

$$TWDBiomass = 0.0042BD^{2.8361} \qquad (6)$$

The analysis resulted in an R^2 of 0.841, an F-statistic of 63.30 (0.000 significance), and no clear pattern in the scatter plot of the residuals. This indicates that the developed allometric relationship is strong and significant, and that the equation produces estimates of the total dry biomass without systematic error. Figure 1 is a graphical depiction of the relationship.

Figure 1: Estimated allometric relationship between total woody dry Jatropha biomass and basal diameter, Tanzania sample



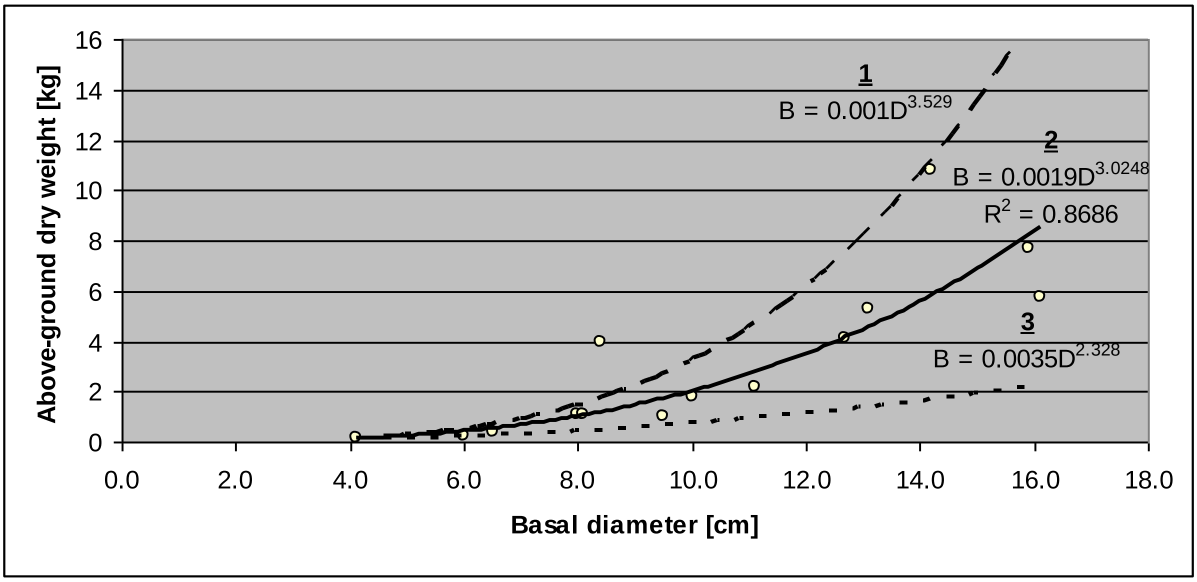
As explained in Section 3.3, it would make sense to distinguish between trees that grew from seeds and cuttings. Unfortunately the sample in this study is not large enough to produce valid equations for both situations separately.

The second allometric equation that was developed identifies the relationship between the basal diameter and the above-ground woody dry biomass:

$$AGWDBiomass = 0.0019BD^{3.0248} \quad (7)$$

The analysis resulted in an R^2 of 0.869, an F-statistic of 79.34 (0.000 significance), and no clear pattern in the scatter plot of the residuals. Similar to the first equation, this indicates that the developed allometric relationship is strong and significant, and that the equation produces estimates of the above-ground dry biomass without systematic error. Figure 2 shows the relationship graphically (Graph 3). This figure also shows the graphs that resulted from the equations that were developed by Ghezehei et al. (2009), and Achten et al. (2010). Both equations were transformed to expressions in centimetres and kilograms, to make a comparison possible. The equation from Achten et al. (2010) were also corrected to exclude the leaf biomass. This was done by subtracting the percentage accounted for by leaves in the total above-ground dry biomass, 43% (Achten et al., 2010), from the total above-ground dry weights that were calculated using their allometric equation. These new values were used to develop a new equation.

Figure 2: Allometric equations between above-ground dry biomass weight and basal diameter from extant research and Tanzania sample



Note: Graph 1 shows the equation from Ghezehei et al. (2009); Graph 2 shows the estimated regression model for the Tanzanian sample. The individual points shown belong to this graph. Graph 3 shows the modified equation from Achten et al (2010) with leaves excluded.

5. Discussion

5.1 Tree characteristics

From the data that were presented in Table 2 it can be observed that there is a clear difference in tree weight between irrigated and non-irrigated trees of the same age. Irrigation is perceived to be a very important predictor for how much and how fast a tree would grow. The sampled unirrigated trees from the driest region produced up to 15 times less biomass than trees of the same age that were irrigated. This is in line with the findings of Achten et al. (2010), who found that *Jatropha* curcas trees stop growing when exposed to extremely dry conditions.

In addition to the important effect of irrigation, the effect of adding extra nutrients should also not be underestimated. According to experiments by Bindraban et al. (2008), adding extra nutrients to a plant under marginal conditions yields a higher effect on a plant's biomass production compared to extra water supply on its own.

When compared to a tree of similar age that was excavated by Firdaus et al. (2010), the trees that were sampled in this study are much lighter. The 32-month old tree of Firdaus et al. (2010) had a total woody dry weight of 16.6 kg, while the heaviest tree of approximately the same age from this study had a dry weight of just over 10 kg. This difference can (most likely) be attributed to two aspects. The first is the climatological difference between Malaysia and Tanzania. Northern Tanzania is much dryer than Malaysia, which would cause a slower growth of *Jatropha* trees, this is confirmed by the data in Table 2 regarding irrigation. Secondly, the trees from this study are often pruned to obtain an optimal shape for biofuel production, whereas the trees from Firdaus et al (2010) were most likely not pruned.

The dry-weight fraction of the trees was determined individually per subsample, this resulted in a mean dry weight fraction of 0.23 grammes per gramme of fresh weight. No significant differences between above- and below-ground parts could be observed. No structural differences could be observed between trees sampled from different places either.

Regarding the root/shoot ratio, one clear conclusion that can be drawn from Table 2 is that it is generally lower for trees that receive more water over their lifetime. From the table it is clear that the trees from the driest environment usually had higher ratios than the irrigated trees. This is in line with the findings from Achten et al. (2010), who identified a root/shoot ratio of 0.27 in wet environments, and one of 0.41 in very dry environments. From the findings of Firdaus et al. (2010) a root shoot ratio also can be calculated. This leads to a ratio of 0.16 for the 32-month old tree, and a similar value for the 17-month old one. This would be in line with the explanation that was already given for the high weights that were reported from that study too. Malaysia has a very wet climate, therefore trees grow quickly and low root/shoot ratios are likely. The lower root/shoot ratios for wetter environments can be explained by a tree sourcing the same amount of water from a smaller volume of soil, compared to a dryer environment. Therefore a smaller root-system is developed. For example, Barton and Montagu (2006) present similar findings and explanations for other species.

5.2 Carbon content and total carbon stock

Our results indicate a low carbon fraction of the Jatropha biomass, which concurs with the results of Firdaus (2010). It would appear that using the 0.5 rule of thumb for estimating the carbon stock could easily lead to overestimation of Jatropha's sequestration potential. The results that were presented in Table 3 also indicate a slight difference between the carbon fractions of the above-ground dry biomass and the below-ground dry biomass. If both averages are calculated (42.5% for below ground, and 44.1% for above-ground) we find a difference of 1.6%. This is again in line with the study by Firdaus et al. (2010), which also indicated slightly lower values for below-ground biomass. In calculating the carbon content of a tree, it is up to the researcher whether one fraction is used for the entire tree, or separate ones for the above- and below-ground parts.

For the purpose of developing a *Jatropha*-based carbon credit project, it might be preferred to use a low fraction, in order to arrive at an overall conservative estimation of the carbon stock. It is wise to adopt a conservative figure in order to prevent a situation in which actual production of credits turns out lower than anticipated at the start of the project. What size a tree will finally reach is difficult to say, and depends on many parameters. Trees that are planted in hedges with small planting distances generally end up being smaller, but the carbon stock per hectare could end up being higher because the density of trees is higher compared to plantations. Planting distances are also important to consider in a plantation model.

A carbon credit project with *Jatropha* curcas will always be combined with biofuel production from its seeds. To be able to harvest the seeds, trees cannot grow too large, so if they grow higher they will most likely be pruned. Trees one through four from the sample that was used in this study have an ideal shape and size for this purpose, and can therefore be used as a standard for this situation. If one knows beforehand that the trees will grow in a drier area, and will remain smaller, other trees from the sample can be chosen to serve as a standard. Pictures of the sampled trees can be helpful in this estimation. These are available on request from the authors. The average total dry woody tree weight of trees one through four is 7.5 kg. If this average would be used in the development of a carbon credit project, every tree would store 3.24 kg of carbon if the average carbon fraction is used. Multiplying this with 44/12, the conversion factor from carbon to carbon-dioxide[1], results in an average 11.86 kg of carbon-dioxide per tree. On a plantation with a common planting distance (2x3m), this would mean a stock of 19.8 tonnes of carbon-dioxide per hectare. If a planting distance of 2x2m is used, the total carbon stock would come to 29.7 tonnes of carbon-dioxide.

[1] This is also used in the official methodologies of the Clean Development Mechanism (cdm.unfccc.int).

5.3 Allometry

Rather than choosing a few reference trees from a sample to estimate carbon stocks, one can use a valid allometric equation for more accurate results. If an appropriate allometric equation is available one can quickly estimate the biomass of trees when the basal diameter is known. A valid allometric equation would save a lot of time and resource-consuming destructive research, which would be essential in the development of successful carbon credit projects with *Jatropha* in the future. They are useful in both the estimation of a project's sequestration potential before it starts, and in monitoring activities after the project gets underway.

The allometric equations that were developed in this study are good predictors for the Jatropha's biomass. The R^2 values that were found indicate a strong relationship, but also show some room for more fine-tuning. This fine-tuning could be done by using a sample of trees that all live under the same circumstances in the same region. This however was not the goal of this study, which was to provide wider applicable equations to serve as a rough indication for project developers while planning a project. Besides selecting more homogeneous ecological circumstances, fine-tuning can also be done by only sampling unpruned trees. This however is not according to the daily reality of biofuel production, which is the scope of this study. This scope does lead to some inevitable variation, and thus a lower R^2, due to the required subjective classification as a "regular" tree for biofuel production.

One can essentially choose which of the two allometric equations to use, and how to use them. In the context of Northern Tanzania, equation (6) will produce valid results, since this is where the samples were taken. However, since the root/shoot ratio tends to differ significantly across different climates and circumstances, it is safer to use equation (7), especially in other contexts. When the root/shoot ratio is known, the below-ground biomass can still be calculated when equation (7) is applied. In this case a smaller numbert of trees can be sampled to determine a valid root/shoot ratio.

If the equation that was developed in this study is compared with the equations from other studies, as was done in Figure 2, it becomes visible that this study's equation forms the middle between the ones developed by Ghezehei et al. (2009) and Achten et al. (2010). That this study delivered lower dry weight values than the one by Ghezehei et al. (2009), can be explained as follows. This study took trees that were used for the production of biofuel as a starting point, and it has been the objective to research the potential for carbon credits combined with biofuel production. This means that it is important that fruits can be easily harvested, and thus that trees need to be pruned at times to get the perfect shape. Ghehezei et al (2009), however, used trees from a university research plot, which were probably not pruned. As was already discussed earlier, this could lead to higher biomasses at similar stem diameters. The study by Achten et al. (2010) already tested their own equation on mature trees, without accurate results. Most likely this is due to their use of very young trees in the development of the equation.

6. Conclusions

This study combined all data that are necessary for the estimation of carbon stocks for development of a carbon credit project with *Jatropha* curcas, and to estimate the contribution of carbon sequestration in Jatropha biomass in greenhouse gas life cycle analyses. These data can be used as reference values in initial project proposals.

The study confirms that the basal tree diameter is a very reliable predictor for the biomass in a tree, both above-ground and for the total tree. It developed highly significant and strong allometric equations for *Jatropha* curcas that can be used in the context of Northern Tanzania. It is likely that the developed equations have the same relevance for all East-African countries that share a similar semi-arid climate. On the other hand, our sample also showed that circumstances under which trees live can also vary significantly, even across short distances. Therefore, we believe that the equation that estimates the above-ground biomass can be more widely applied than the equation for the total biomass.

The main limitation of this study is the limited number of sampled trees. This study aimed at developing knowledge at an indicative level. Statistically significant samples of trees still need to be taken at the exact locations where Jatropha projects are developed. This study can only be helpful to provide rough estimations regarding the carbon sequestration potential of *Jatropha* curcas*.*

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