Master Thesis

Availability and cost of agricultural residues for bioenergy generation

International literature review and a case study for South Africa

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2 Executive summary

Background
The sustainability of first generation bioenergy has been researched intensively due to problems resulting from land use change. There is a growing interest to use agricultural residues for bioenergy production as they can be a sustainable feedstock available at low cost since residues are regarded to be a by-product. Many studies on the potential to use residues for energy purposes have been conducted but results vary widely. The differences arise from a poor understanding of the factors affecting residue potentials. Especially the amount of the produced residues that can be removed without negatively affecting soil productivity and the demand for residues by competing uses is usually estimated rather than calculated.

South Africa has a heavy CO_2 footprint due resulting from its coal dependence; coal produces 88% of the country's electricity. Using agricultural residues for bioenergy production could be an option to move away from this dependence and reduce its CO_2 footprint. Besides, converting biomass into transport fuels can help improve the energy security since the country is now fully dependent on oil imports.

Goal and Scope
This master thesis consists of both a literature review and case study for South Africa. The focus in both parts is on understanding how the supply and cost of residues is affected by the factors and how this varies under different conditions. Only for the case study actual potentials and cost are calculated. This thesis assess 1) the theoretical potential: the total amount of residues produced. 2) the sustainable potential: the amount of residues that can be removed from the land without decreasing soil productivity 3) the technical potential: the sustainable potential minus the demand for residues by competing uses and 4) the supply cost at farm gate. This is done for maize stover, wheat straw, sugar cane tops and trash and sugar cane bagasse.

Methodology
The calculation of the amount of residues produced (**theoretical potential**) is straight forward and is done based on the crop yield, residue-to-product ratio, area under cultivation and moisture content HHV_{dry}.

The calculation of the **sustainable potential** is less straight forward. The removal of residues is considered sustainable as long as the soil productivity is not reduced; two criteria are chosen to ensure this. 1) a residue cover of 2 tonne/ha must be present to control erosion; leaving more residues has only a marginal effect. 2) Enough residues (accounting for both above and below ground residues) must remain in the field to maintain a 2,0% SOC in the top 20 cm of the soil. This amount was dependent on local conditions and was modelled using the Rothamsted Organic Carbon Model. Summarizing, a minimum of 2 tonne residues/ha must be left in the field and depending on the local conditions an additional amount of residues may be required to maintain 2,0% SOC.

Regarding the **technical potential**, the demand for residues by competing uses was calculated based on the size of the livestock population and estimates of the percentage of the livestock using residues and the duration of the winter period when the livestock can not graze on the pastures.

The **supply cost at farm gate** are calculated based on the direct cost and the indirect cost. The former are the extra cost the farmer faces for harvesting the residues and the latter the compensation for removed nutrients. The harvest cost of conventional harvest where crop and residues are harvested separately are compared with innovative harvest methods which harvest both the crop and residues in a single pass.

2.1.1 Results

Theoretical potential
The theoretical potential is calculated on a provincial level resulting in a total potential of 267 PJ for South Africa, 161 PJ resulting from maize stover, 52PJ from sugar cane bagasse, 34 PJ from wheat straw and 20 PJ resulting from sugar cane trash. See Figure 1.

Furthermore a relation between the residue-to-product ratio and the crop yield was found for maize stover, wheat straw and sugar cane trash, stating that the relative residues production declines for increasing crop yields. At last, averages for the HHV_{dry} and the moisture content are calculated from literature.

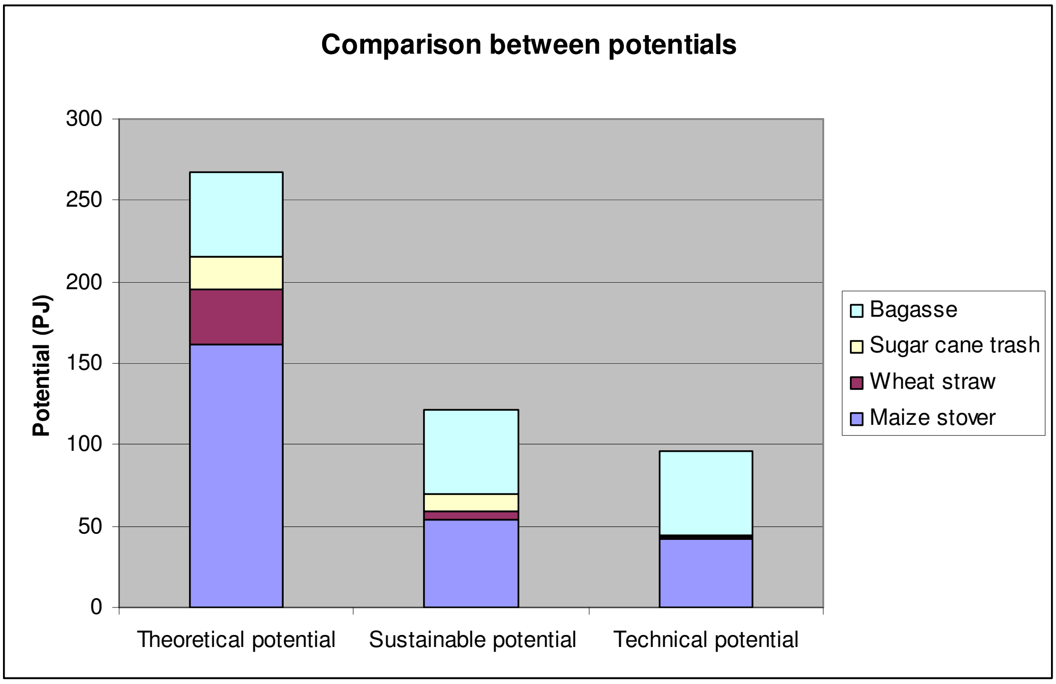

Figure 1: Comparison between the theoretical potential (267 PJ), sustainable potential (121 PJ) and technical (96 PJ) potential, showing the contribution of the residue types to the totals.

Sustainable potential
The sustainable potential for South Africa is calculated to be 121 PJ (See Figure 1), less than half of the sustainable potential, limited by both the residue cover required to control soil erosion and the residues required to maintain a 2,0% SOC level.

Technical potential
14% of the sustainable potential is demanded by animal uses, resulting in a technical potential of 96 PJ, consisting half of bagasse (for which all potentials are equal) and half of maize stover.

Supply cost
Harvesting residues using single pass harvest proved to be the cheapest way to harvest maize and wheat residues with total cost as low as 0,78 U.S. $/GJ for maize stover and 0,60 U.S. $/GJ for wheat straw, including a respective nutrient compensation cost of 0.11 U.S.$/ GJ and 0.08 U.S.$/GJ .For sugar cane trash the cheapest way to harvest residues them conventionally in round bales, costing 0.67 U.S.$/GJ, including 0.06 U.S.$/GJ. Sugar cane bagasse is available at zero cost at sugar mills.

2.1.2 Conclusions for South Africa

Available potential
It is concluded that the selected residues can potentially account for ~1.5% of South Africa's primary energy demand. However, since this potential is scattered over a large area and since transport cost tend to increase with distance the potential that is economically feasible will be smaller.

About half of the technical potential consists of maize stover. 17 PJ of the stover is located favourably in Mpumalanga as most coal fired power plants as well as SASOL's coal to liquids facility is located here. Another 17 PJ is located in the Free State and can potentially be co-fired in one of the coal fired power plants in the province. The 52PJ of bagasse potentially available is currently very inefficiently used to produce the sugar mills internal power demand; this should only require 20% - 30% of the produced bagasse. But since there is no market for bagasse and buyback rates for electricity are non-existent, there is no incentive for the mills to install more efficient boilers.

Increasing the available potential
Banning open field burning prior to sugar cane harvest would make an additional 8.5 PJ available. This could for instance be converted into electricity by the sugar mills thereby offsetting coal based electricity production, preventing the emissions from open field burning and positively affect soil productivity. **Double cropping** is another attractive option as it was calculated to reduce required annual residue inputs between 11 and 24%. Moreover the amount of above as well as below ground residues is increased and it is beneficial for soil quality. This makes it a very attractive option for areas not limited by water availability, unfortunately these are sparse in South Africa (du Preez 2012).

Supply cost
The supply cost for South Africa compare favourably to cost in the U.S.A., Europe and Brazil. Coal is priced at 1,90 U.S. $/GJ in South Africa, taking residue transport cost into account the residue supply cost is typically more expensive when the transport distance exceeds 30km's. However the reverse is true for crude oil. Due to the important reliance the price is about 6,5 U.S.$/GJ. If the residues have to be transported for 50 km's they can be delivered at 3 – 4 U.S.$/GJ and refined for an additional 1 – 2 U.S.$, residues can compete with oil.

2.1.3 General conclusions

RPR varies according to yield
There is a relation between crop yield and RPR, for high yields the RPR is relatively low and vice versa.

High yields required
The amount of residues required to maintain soil productivity is not dependent on the crop yield. This implies that in areas where high yields can be achieved the sustainable potential will be high.

Low yields: SOC limiting; high yields: erosion limiting
The sustainable potential is affected by the amount of residues required for erosion control (2 tonne/ha) and the amount of residues required to maintain 2,0% SOC (variable). For South Africa the residue cover required for erosion control becomes limiting when the crop yield exceeds ~4 tonne/ha for maize and wheat and ~60 tonne/ha for sugar cane. Although the thresholds will vary for different areas, the general principle, stating that for low crop yields the residues required to maintain SOC levels are limiting and for high yields the required erosion cover is limiting, holds.

Animal uses
It is important to consider the demand for residues by animal uses (calculated based on the livestock population) and the amount lost by open field sugar cane burning. However, in South Africa this demand is relatively large (14% of the sustainable potential) compared to the U.S.A. where demand is typically less than 5%.

Double cropping
As discussed above double cropping reduces that required residue inputs by 11% to 24% compared to growing continuous maize or wheat. With the additional benefits of higher residue production and improved soil quality this is a win-win situation.

Supply cost - Promising new harvest methods
Innovative new harvest methods are already the most cost-effective way to harvest residues and since these technologies are all very new, cost are expected to decrease as learning and scaling effects kick in. Qualitatively there are two major benefits. First, since the residues are not contaminated with dirt the ash content is generally 5 percent point lower. Second, the single pass harvest methods allow the farmer to choose the amount of residues he wants to remove which is not possible with conventional harvest methods, this is quite important as it is not sustainable to remove all the residues from the field.

Cost decrease when harvesting a larger percentage of residues
In general the residue supply costs at farm gate are found to decrease when an increasing percentage of the residues is harvested.

3 Introduction

3.1 *Background and justification*

Role for bioenergy in global energy supply
There is a need for renewable energy resources as an alternative to fossil fuels. The global demand for energy keeps rising while the fossil fuel reserves are running out, pushing up the energy prices. Furthermore the use of these fossil resources contributes to climate change (IEA 2009). Biomass is considered to become a major contributor to the global primary energy supply. Studies on the future contribution of biomass in 2050 vary widely with the lowest estimates below 100 EJ/yr and the highest above 400 EJ/yr (Berndes, Hoogwijk & van den Broek 2003).

Importance of residues
There are concerns about the sustainability of bioenergy. The problems are mostly due to land use change. When produced unsustainable, biomass production can lead to the replacement of food crops by energy crops or deforestation (Evans, Strezov & Evans 2010). This has negative environmental, ecological and social impacts. The use of agricultural and forestry residues for bioenergy production is a possible solution to this on-going debate as these can be used without threatening the global food supply (Hoogwijk et al. 2003); (Smeets et al. 2007).

According to the IEA (IEA 2010) it could be the most sustainable feedstock for bioenergy production. Moreover, agricultural residues are the most significant low-cost source of cellulosic plant material, with corn and wheat straw being the most plentiful sources (Perlack, Turhollow 2003).

Knowledge gap
The potential to use residues for bioenergy generation has been studied on both a national and global scale resulting in varying potentials. According to a review by Hoogwijk et al. (Hoogwijk et al. 2003) the global potential spans from 20 to 48 EJ/yr whereas Smeets et al. (Smeets et al. 2007) calculate the potential in 2050 to be between 76 and 96 EJ/yr (roughly between 5% and 20% of global primary energy supply). These differences are to a large extent explained by the variation in assumptions on the sustainable availability of residues and other factors determining the potential.

Quoting Wilhelm et al. (Wilhelm et al. 2004) "Agronomist are challenged to develop a procedure for recommending maximum permissible removal rates that ensure sustained soil productivity". Such a procedure hasn't been developed yet. Besides the availability of residues, studies also use varying residue-to-product-ratio's to calculate the production of residues. This study could contribute to this development by assessing how the factors that determine residue supply and cost are differ under varying conditions.

South Africa
Euler (Euler 2010) successfully completed a holistic study of the possibility for a large scale South African bio-energy industry looking at residues and wastes as well as energy crops. The potential from residues and wastes was calculated to be between 440 and 570 PJ/yr. This potential availability together with the fairly well developed transport system and one of the world's leading coal to liquids facility cause Euler (Euler 2010) to conclude that bio-energy production from residues is an interesting option for South Africa.

However, also the study by Euler had to cope with the difficulties of estimating the production of residues and the maximum removable rates of residues, possibly leading to uncertainties in the results.

Literature review and case study
This study will review the relevant literature to see whether it can be derived how the supply and cost of residues depends on different factors. If these relations are found, they can be used in the case-study to calculate actual potentials for South Africa. On the other hand, gaps in literature may be filled with what is learned from the case study.

3.1.1 *Background on South Africa*

Drivers
From a South African perspective main drivers to take on bio-energy are environmental concerns and the energy security deficiency. Both of these issue stem from South Africa's dependency on coal. Besides these two main drivers the utilization of residues as a feedstock for energy production can provide an opportunity to stimulate rural development which is a key objective in South Africa (Mangoyana 2009).

Natural resources
South Africa has enormous coal reserves which rank as the world's sixth largest. Coal amounts to about 71.1% of the country's primary energy needs[1], see Figure 2 (IEA 2008). Besides coal, there are little natural resources, the country has virtually no crude oil resources and only limited natural gas reserves. This forces South Africa to import 95% of the crude oil consumed. Part of the demand for refined petroleum products is met by converting coal to liquids which is done by SASOL and by converting natural gas to liquids, which is done by PetroSA (South African Government 2011). The most used source of renewable energy is traditional biomass (4.4% of primary energy supply) and a small contribution comes from bagasse (1.1% of primary energy supply) which is co-fired in private power plants that produce electricity and steam for sugar milling (Winkler 2005).

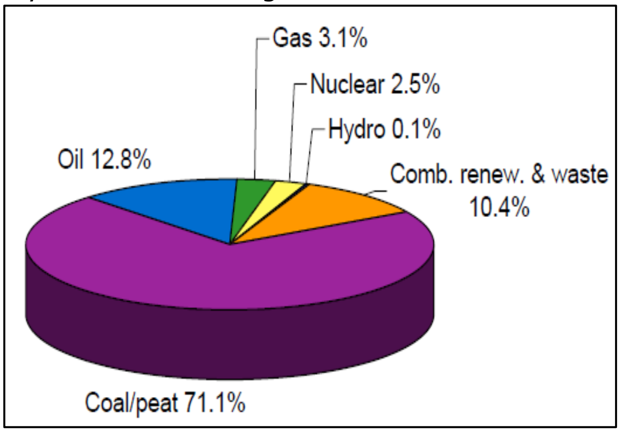

Figure 2: Breakdown of the total primary energy supply into the different resources {{115 IEA 2008}}

Environmental concerns
The reliance on coal combined with a strong economic growth and low energy conversion efficiencies makes South Africa the biggest emitter of Africa and one of the world's 20 most emitting countries of greenhouse gasses (South African Government 2011). Looking at the emissions per unit of GDP South Africa is quite high, 1.84 kg CO_2/ 2000 USD for South Africa compared to the global average of 0.73 kg CO_2/ 2000 USD (IEA 2008). The environmental and energy security

[1] The total primary energy supply of South Africa is 5.63 EJ (IEA 2008)

problems are the main reason for the South African government to adopt the National Climate Change Strategy (South African Government 2011).

3.2 *Research aim and research questions*

3.2.1 *Research aim*

This thesis aims to investigate how the production, availability and supply costs of agricultural residues for energy purposes are influenced by the key determining factors.

As mentioned the study will consist of both a literature review and a case-study. The major difference between these two is that only in the case study the actual potential will be calculated. The literature review will solely assess how different factors influence residue production and availability for bioenergy generation.

3.2.2 *Research questions*

Main research question:
How do the key factors affect the theoretical and technical potential for sustainable bioenergy generation from maize, sugar cane and wheat residues and the cost at which these residues can be supplied?

This question can be divided into sub questions a and b which concern the international literature review and sub questions c, d, e and f which concern the case study for South Africa.

Sub questions concerning the literature review:

a) How do the key factors affect residue production and availability for sustainable bioenergy generation from maize, sugar cane and wheat residues and how can these factors be parameterized?

b) How do the key factors affect the supply costs for sustainable bioenergy generation from maize, sugar cane and wheat residues and how can these factors be parameterized?

Sub questions concerning the case study for South Africa:

c) What is the theoretical potential for bioenergy generation from maize, wheat and sugar cane residues in South Africa?

d) What is the technical potential for sustainable bioenergy generation form maize, wheat and sugar cane residues in South Africa?

e) What are the supply cost of maize, wheat and sugar cane residues in South Africa?

f) Which options exist to increase the availability and decrease the costs of maize, wheat and sugar cane residues for sustainable bioenergy generation in South Africa?

4 Methodology

The goal of this chapter is to provide a theoretical framework which is used to answer the research questions defined in section 3.2.2. It is important to note that the working procedures (section 4.5) are used in the case study to calculate actual figures, where the literature review only looks into the factors influencing residues supply and cost.

4.1 *Boundaries*

This study will solely look into the supply side of bioenergy production. It is assumed that there is a demand for residues, provided they can be produced at competitive costs

Region
The literature review will not be confined to a specific region but will determine the different factors and constraints of residue production and utilization for energy purposes on a global scale. The case study will assess the potentials and costs for South Africa, on a provincial scale.

Commercial vs communal farms(Hove 2012)(Hove 2012)
A substantial part of agricultural production results from subsistence farming, but since the crop yields in this communal sector are typically very low (<2tonne/ha) it is not included in this study. When yields are this low, all the available residues should be left on the ground for soil conservation purposes {{208 Hove, L. 2012}}.

Crop selection
The crops included in this study, literature review and cases study, are sugar cane, maize and wheat. These crops have the highest production in South Africa, apart from potatoes and grapes but these are not interesting from a residue perspective (based on FAOSTAT 2012). On a global scale these crops are among the four crops with the highest production together with rice. For the sake of comparison the same crops are assessed in the literature review and case study, therefore rice is excluded from this study

Residue types
Of all three crops harvest as well as process residues are included (for definitions of these residue types see section 4.4). Regarding the process residues, only bagasse from sugar cane is included since in commercial farming maize and wheat production does not generate any process residues. Both crops are harvested using combine harvesters which combine the harvest of the crop with the processing to retrieve the main produce, maize and wheat kernels. Considering sugar cane, the main produce is sugar which is produced in processing factories where bagasse is produced as a by-product. One could also argue that distillers grain is a process residue of maize since it is a by-product of ethanol production, still it is not included in this study since the maize kernels are generally considered to be the end product of maize production.

4.2 Data collection

Regarding the literature review the data is collected from articles in relevant published journals as well as grey literature. For the case-study, expert opinion is used in addition to these two sources.

4.3 Defining potentials and supply cost

The definitions of the theoretical and technical potential are based on Smeets et al. (Smeets et al. 2007, Smeets et al. 2006). Besides these two potentials, also a sustainable potential is defined.

a) *Theoretical potential*: The upper limited of bioenergy production from residues, limited by fundamental physical and biological constraints and the current production of agricultural crops.

b) Sustainable potential: The fraction of the theoretical potential that can be removed without negatively effecting soil health[1].

c) Technical potential: The fraction of the theoretical potential that can be produced sustainably given the level of technical advancement and that is not limited by competing uses of residues.

d) Residue supply cost at the farm gate: The cost for all field operations required to collect the residues and supply them at the edge of the field in a way suitable for short range transport.

It is useful to include the sustainable potential as this shows what can be removed sustainably not considering competing uses. Whether a farmer sells his residues for energy purposes or as e.g. animal bedding will most likely be fully dependent on who is willing to pay the highest price.

It is noted that no cost for crop cultivation are allocated to the residues as they are considered to be a by-product.

4.4 Defining residue types

In this study, harvesting as well as processing residues will be included. The two different types of residues are defined as:

Harvest residues: All the above ground biomass other than the main produce.

Process residues: Residue biomass created when the crops are processed into marketable products.

	Maize	**Sugar cane**	**Wheat**
Harvest residues	Stalks, leaves and cobs*	Tops, green and dry leaves	Straw and chaff
Process resdiues	-	Bagasse	-

Table 1: Identification of the different types of residues per crop. * with cob the residual part of the maize cob is meant that remains after the kernels are stripped off.

Table 1 categorizes the different parts of the three selected crops. In the past studies also distinguished process residues for maize and wheat but with the introduction of the combine harvester which combines harvesting and processing of the crop, the process residues are no longer a separate residue stream for maize and wheat. Since there are no combine harvesters for sugar cane and processing happens in a factory, sugar cane does have separate process residues commonly called bagasse.

[1] It is assumed that the soil health is maintained as long as soil organic carbon levels are maintained at a minimum of 2,0% (see section 9.1.1) and erosion is reduced below 10% of the bare soil erosion (see section 6.1.2.1.2).

4.5 Working procedures

To calculate the actual residues potentials and cost in the case study, the following procedures are followed. Note, again, that only in the case study actual potentials are calculated.

4.5.1 The theoretical potential

Equation 1 is used to calculate the theoretical potential of the harvest as well as the process residues, for each residue type a different residue-to-product ratio is used though (so in total 4 RPR's are used), see below.

$$THP = Y * RPR * A * (1 - MC) * HHV_{dry}$$

Equation 1. Theoretical potential for harvest residues.

Where:
$THP_{harvest}$: Theoretical potential of the harvest residues in GJ.
Y: Yield of main produce in t_{fm}/ha.
RPR: Residue-to-product ratio of harvest residues
A: Production area in ha.
MC: Moisture content as a percentage of the fresh matter.
HHV_{dry}: Higher heating value of the residues in GJ/t_{dm}.

Defining residue-to-product ratio's
Two different residue production ratios will be used, the harvest residue production ratio and the process residue production ratio[1]:

- *The harvest residue-to-product ratio*: The fresh weight of the above ground residue biomass that remains in the field following crop harvest divided by the fresh weight of the agricultural product

- *The process residue-to-product ratio*: The fresh weight of residue biomass produced when processing the agricultural product divided by the fresh weight of the agricultural product

4.5.2 Sustainable and technical potential

4.5.2.1 Sustainable potential

The sustainable potential is calculated using Equation 2 for the harvest residues, for the process residues the sustainable potential is identical to the theoretical potential. The sustainable potential is calculated on a provincial level.

If S>E: $SP_{harvest} = THP_{harvest} - (S * A * HHV_{dry})$

If S<E: $SP_{harvest} = THP_{harvest} - (E * A * HHV_{dry})$

Equation 2. Calculation of the sustainable potential for harvest residues.

Where:
$SP_{harvest}$: Sustainable potential of the harvest residues, in GJ/ha
$THP_{harvest}$: Theoretical potential of the harvest residues calculated using Equation 1, in GJ.

[1] Only used for sugar cane bagasse, see section 4.1.

S: Residues required to maintain 2,0% SOC calculated with the Rothamsted Organic Carbon Model, in t_{dm}/ha (see section 6.1.2.1.2).
E: Soil cover required to reduce erosion to 10% of the bare soil erosion, in t_{dm}/ha (see section 9.1.1).
A: Production area in ha.
HHV_{dry}: Higher heating value of the residues in GJ/t_{dm}.

Defining Residues required maintain soil productivity
Based on the literature review and the functions of agricultural residues, maintaining soil productivity is defined based on two criteria (see section 9.1). First, soil erosion must be reduced to a maximum of 10% of bare soil erosion, see section 6.1.2.1.1. Second, a minimum soil organic carbon level of 2,0% must be sustained, see section 9.1.1. Residues play a vital role in sustaining agricultural production systems, where they have 5 main functions, see section 6.1.1.1. However, if enough residues are present to prevent soil erosion and maintain soil organic carbon levels, then it is safe to assume that the other functions are also preserved since these functions require less residue inputs.

Calculation of the residues required to maintain soil organic carbon levels
The amount of residues required to maintain soil organic carbon levels at a minimum of 2,0% under various conditions is calculated with the Rothamsted Organic Carbon Model. See appendix A.

4.5.2.2 Technical potential

The technical potential is calculated using Equation 3 and Equation 4 for the harvest and process residues respectively.

$$TP_{harvest} = SP_{harvest} - (DCU_{process} * HHV_{dry})$$

Equation 3. Calculation of the technical potential for process residues.

$$TP_{process} = SP_{process} - (DCU_{process} * HHV_{dry})$$

Equation 4. Calculation of the technical potential of the process residues.

Where:
$TP_{harvest}$: Technical potential of the harvest residues in GJ
$TP_{process}$: Technical potential of the process residues in GJ
$Sp_{harvest}$: Sustainable potential of the harvest residues, calculated according to Equation 3, in GJ.
$SP_{process}$: Sustainable potential of the process residues calculated according to Equation 4, in GJ.
$DCU_{process}$: Demand by competing uses in t_{DM}.
HHV_{dry}: Higher heating value of the residues in GJ/t_{dm}.

Defining the demand for residues by competing uses.
The competing uses are all off-field, non-energy uses of agricultural residues Below, three different non-energy uses for residues are listed, the most important being farm and animal use. (Kadam, McMillan 2003):

1. Farm and animal uses[1]. Residues can be used as (often low value) feed for cattle or as animal bedding.
2. Biobased materials:
    a. Composite products.

[1] This does not include the residues that remain in the field for nutrient cycling and to prevent soil erosion.

   b. Pulp and paper.
3. Miscellaneous. Residues can be composted with manure to produce potting soil, spread along roadsides to prevent soil erosion or similarly for slope stability.

Since the farm and animal uses are by far the most important, this is the only competing use taken into account.

Calculation of the residue demand by competing uses
The procedure for the calculation of the residue demand by competing uses is an outcome of the literature review and is shown in sector 6.2 but is principally calculated based on the size of the livestock population, and the demand for feed and bedding during the winter period when the animals cannot graze in the field.

Loss of sugar cane tops and trash from burning
Obviously, when sugar cane is burnt prior to harvest, the tops and trash are lost. To account for this, only the sugar cane production area where burning is not practiced is used to calculate the technical potential.

4.5.3 Residue supply cost

The aim is to determine the cost of the most cost-efficient residue collection system. Costs are divided in direct and indirect cost and expressed in 2011 U.S.$/GJ. The direct costs are calculated by adding the cost of the different operations required to harvest and transport the residues, such as chopping, baling and bale transport. The indirect cost are the compensation a farmer requires for the loss of nutrients as an effect of harvesting the residues.

Furthermore, it is stressed that in the cost calculations the most efficient machinery is considered. Since large scale bioenergy production is not realized yet, it is important to consider to most efficient options to gain insight into the possibilities for the future. In practice this would mean that farmers have to share equipment amongst each other as the most efficient equipment is generally the equipment with the highest capacity and it is typically not economical for a single farmer to own a machine with such a high capacity. Equipment sharing can cause problems when the harvest window is narrow, however this is not taken into account in this study.

The total annual cost are calculated according to Equation 5.

$$CFG = (I + R\&M + F\&L + L) * (1 + P) + NCC$$

Equation 5: Calculation of the total cost at farm gate.

Where:
CFG: Cost at farm gate ($/tonne).
I: Annualized investment cost ($/tonne).
R&M: Repair and maintenance cost ($/tonne).
F&L: Fuel and lubrication oil cost ($/tonne).
L: Labor cost ($/tonne).
P: Profit margin (%).
NCC: Nutrient compensation cost ($/tonne).

4.5.3.1 Direct cost

To calculate each of the different cost components, the following procedures are used.

4.5.3.1.1 *Investment cost*

The investment cost are one-off cost and thus need to be annualized (see Equation 7) before they can be converted into cost per tonne. Calculation was done according to Equation 6.

$$I = \frac{PP * \alpha}{AU/C}$$

Equation 6: Investment cost

Where:
I: investment cost ($/tonne)
PP: Puchase price ($)
α: Annuity factor, calculated according to Equation 7 (yr^{-1})
AU: Annual usage (h/yr)
C: capacity in (tonne/h)[1]

$$\alpha = \frac{r}{\left(1-(1+r)^{l}\right)}$$

Equation 7: Annuity factor

Where:
α: Annuity factor (yr^{-1})
r: Real interest rate (%)
l: The lifetime (yr)

4.5.3.1.2 *Repair and maintenance cost*

The money spent on repair and maintenance during the life time of the machine are usually calculated as a percentage of the purchase price. (). The standardized percentages as used for each machine type in this study are shown in Table 2.

$$R\&M = \frac{R\&MP * PP * \alpha}{AU/C}$$

Where:
R&M: Repair and maintenance cost ($/tonne)
R&MP: Repair & maintenance percentage; percentage of the purchase price spend on repair and maintenance during the life span of the machine, see Table 2.
PP: Purchase price ($)
α: Annuity factor, calculated according to Equation 7 (yr^{-1})
AU: Annual usage (h/yr)
C: capacity in (tonne/h)

[1] When the capacity was given in ha/h, this was converted to tonne/h by multiplication with the yield (tonne/ha).

Machine	R&M cost
Tractor (4wd)	80%
Combine harvester	40%
Mower	150%
Windrower	55%
Rake	60%
Baler (large square)	75%
Baler (large round)	90%
Bale mover[1]	80%
Trailer[1]	50%

[1] Assumed

Table 2: The percentage of the purchase price spend on repair and maintenance during the life span of the machine. Adopted from {{181 Turhollow, A. 2009}}.

4.5.3.1.3 *Fuel and lubrication oil cost*

The fuel consumption is not generally available for machinery and if stated it is dependent on the operation mode. For example, if a 50 kW tractor is used to pull an implement that only requires 20 kW the fuel consumption is obviously lower then pulling an implement requiring the full 50 kW. To get around this problem a uniform fuel consumption per kWh is assumed; 0.22 l/kWh (Turhollow, Wilkerson & Sokhansanj 2009). Furthermore for each implement, a tractor that closely matches its power demand is chosen.

The cost for lubrication oil is assumed to be 15% of the fuel cost(Turhollow, Wilkerson & Sokhansanj 2009).

$$F\&L = \frac{FC * P * FP}{C} * (1 + L)$$

Equation 8: Fuel cost.

Where:
F&L: Fuel and lube cost (U.S.$/tonne)
FC: Uniform fuel consumption per kWh is assumed; 0.22 l/kWh (Turhollow, Wilkerson & Sokhansanj 2009)
FP: Fuel price in $/L.
P: Power (kW)
C: Capacity in (tonne/h)
L: Lubrication oil cost as a percentage of the fuel cost (%).

4.5.3.1.4 *Labor cost*

Labor is required to operate the machinery but also for the preparation, cleaning and storage of machinery, therefore a factor is applied to the machine operating hours to take this into account. This factor is assumed to be 1.2 man hours/machine hour (Sokhansanj, Turhollow 2002). The Labor cost in ($/tonne) are calculated …….

$$L = \frac{1.22 * W}{C}$$

Equation 9: Labor cost

Where:
L: Labor cost ($/tonne)
W: Wage rate ($/h)
C: Capacity (tonne/h)

4.5.3.1.5 *Farmer profit margin*[1]

At last, the farmer needs to have an incentive to put in the extra work to harvest the residues, a profit margin. This profit margin is assumed to be 10% (Sokhansanj, Turhollow 2002).

4.5.3.2 Indirect cost

4.5.3.2.1 *Farmer compensation for lost nutrients*

Agricultural residues contain a certain amount of vital nutrients, mainly nitrogen, potassium and phosphorous (Gallagher et al. 2003). These nutrients are removed with the residue harvest. Since the farmer must make up for this nutrient loss by adding additional fertilizer in order to maintain yields, he must receive a financial compensation.

Just like nutrients form fertilizer, the nutrients released from crop residues are not fully recovered by plants. The released nutrients are susceptible to leaching (N), denitrification (N), immobilization (N, P and K) and fixation (P and K). The efficiency of nutrient uptake by plants from fertilizer or crop residues is assumed to be similar, therefore it is assumed that the amount of residues removed with crop residues must be compensated by a similar amount of fertilizer.

The nutrient compensation cost are calculated according to Equation 10:

$$NCC = NC * FC$$

Equation 10: Calculation of the nutrient compensation cost.

Where:
NCC: Nutrient compensation cost (U.S.$/tonne)
NC: Nutrient content (tonne/tonne)
FC: Fertilizer cost (U.S.$/tonne)

4.5.3.3 Allocation of cost

As mentioned, residues are regarded as a by-product and therefore no costs for growing the crop are allocated to the residues. However, in some cases harvesting the residues slows the harvesting of the main crop, thereby increasing the cost. In that particular case, this cost increase must be allocated to the residues. This is the case when the capacity of the combine harvester is reduced because it is also used to power for example an attachment harvesting the resdiues or pulling a baler. These additional costs are calculated by first subtracting the cost of main produce harvest at full capacity from the cost of harvest at reduced capacity and then multiplying the difference by the combine process ratio between residue and main produce and residue. Which states the

[1] The profit margin is only calculated over the direct cost. The indirect cost are a compensation in cost, while the profit margin is a financial incentive for the farmer to carry out the extra field operations to harvest the residues.

ratio at which grain and resiude are processed in the combine harvester. See Equation 11.

$$AC = (HD - HF) * PR$$

Equation 11: Calculation of the additional harvest cost for main produce harvest as an effect of a capacity reduction of the combine harvester because it needs to power residue harvesting attachments.

Where:
AC: Additional harvest cost (U.S.$/tonne residue)
HD: Harvest cost at decreased capacity (U.S.$/tonne main produce)
HF: Harvest cost at full capacity (U.S.$/tonne main produce)
PR: Process ratio between residue and grain ((tonne main produce/h)/(tonne residue/h).

Part 1: Review of international studies on bioenergy generation from residues

The potential for bioenergy generation from agricultural residues is being studied intensively and many studies have been conducted on both a regional and a global scale. Often the outcomes of these studies vary considerably because the factors, such as the residue to product ratio and the sustainable removable amount of residues, used to calculate potentials range substantially.

As an example, Hiloidhari assumes a RPR of 2 for maize (Hiloidhari, Baruah 2011b), whereas the IEA uses a RPR of 1.5 (IEA 2010) and Kim et al. assume a ratio of 1 (Kim, Dale 2004). Similarly the percentage of the produced residues that can be removed in a sustainable manner ranges from 20% (Hiloidhari, Baruah 2011a) to 50%(Fischer et al. 2007) and even 70%(Euler 2010). Obviously this has a large impact on the resulting potential for bioenergy production.

The aim of this review is to study if the differences as described above can be explained by comparing the local conditions of the different study and to see what relations there are between the local conditions and the key parameters. Chapter 4 and 5 discuss the key factors determining the theoretical and technical potential respectively. Chapter 6 looks into the key factors determining the supply cost.

5 Factors influencing the theoretical potential

As discussed in section 4.5.1 the theoretical potential is calculated from the crop yield, the residue-to-product ratio, the moisture content and the higher heating value according to Equation 1. The yield is not discussed in this chapter since the yields for different crops around the world are well documented. A discussion of the three other factors can be found in the sections below.

5.1 Residue-to-product ratio

The amount of residues produced, and thus potentially available for bioenergy production, is calculated using the residue-to-product ratio, defined in section 4.5.1. As pointed out above there are significant differences between RPR's used in different studies however recent studies generally assume an average ratios of 1 (maize); 1.3 (wheat); 0.3 (sugar cane bagasse) and 0.15 (sugar cane tops and trash) (Perlack, Turhollow 2003, Kim, Dale 2004, Hiloidhari, Baruah 2011a, Nelson et al. 2004, Nelson et al. 2004, Jingura, Matengaifa 2008, Macedo, Leal & Hassuani 2001, Purohit 2009).

In reality the residue-to-product ratio is not constant. It depends on the yield on the one side but also on stresses the crop experiences during growth, for instance caused by draught. In the following sections the dependence of the RPR on these factors will be discussed. It is important to note that all studies which assume a certain RPR are excluded from the analysis, only studies which actually measured (or refer to studies which measured) both crop and residue harvests are included.

5.1.1 Maize and wheat

5.1.1.1 Relation between RPR and yield

According to Fisher et al. (Fischer et al. 2007) there is an inversed linear relation between the RPR of maize and the yield. For high yields (>9 tonnes/ha) the RPR is 1.0, and for low yields (<1.5 tonnes/ha) the ratio is 2.0. For wheat the RPR is 0.7 for yields exceeding 9 tonnes/ha and 0.75 for yields below 1.5 tonnes/ha. However, these ratios are to a large extent based on an article by Koopmans and Koppejan (Koopmans, Koppejan 1998) which is based on measurements, dating from 1979 to 1991.

Scarlat et al. (Scarlat, Blujdea & Dallemand 2011b) assessed the relation between the RPR and the yield for maize and wheat separately, for yields ranging between 1 and 11 tonnes/ha. The results are shown in Figure 3. The trend line for these data points can best be described by Equation 12 and Equation 13 indicating that the ratio declines for increasing yields.

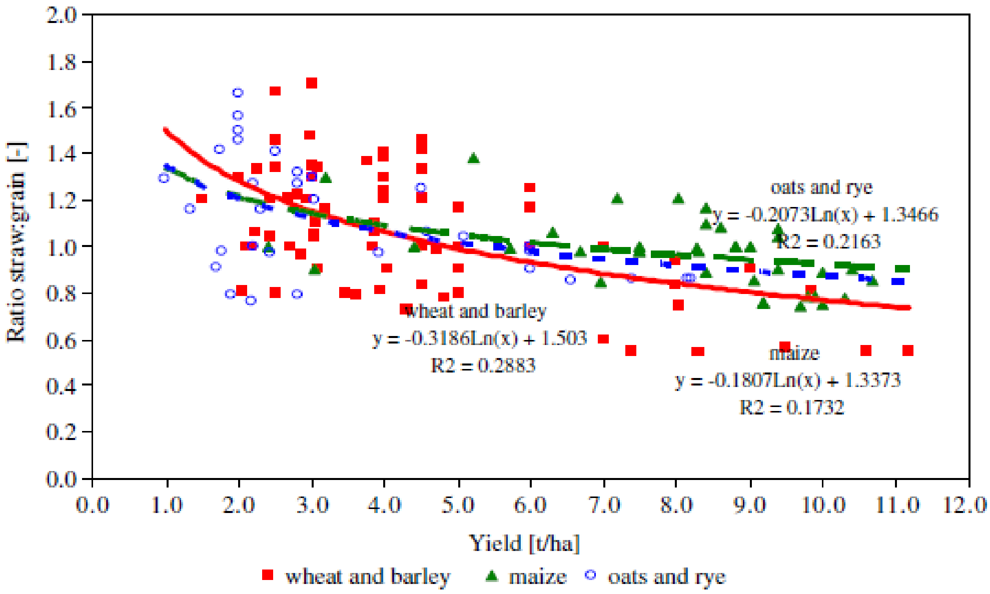

Figure 3: Residue production ratio as a function of yield for cereals {{81 Scarlat,N. 2011}}

$$RPR_{maize} = -0.1807\ln(yield) + 1.3373\,;$$

$$\mathbf{RPR_{maize}} = -0.1807\ln\left(\text{yield}\left(\frac{t}{ha}\right)\right) + 1.3373; \quad R^2=0.17$$

Equation 12: RPR for maize as a function of grain yield (tonne/ha) and the R^2 value of the trend line.

$$RPR_{wheat} = -0{,}31861\ln(yield) + 1{,}503$$

$$\mathbf{RPR_{wheat\ and\ barley}} = -0.3186\ln\left(\text{yield}\left(\frac{t}{ha}\right)\right) + 1.503 \quad ; \quad R^2=0.29$$

Equation 13: RPR for wheat as a function of grain yield (tonne/ha) and the R^2 value of the trend line.

Linden et al. (Linden, Clapp & Dowdy 2000) experimentally measured maize yields and RPR's for different tillage and residue removal treatments and plotted the results. They measured decreasing RPR's for increasing crop yields. They report high RPR's of 1.5 for yields of 5 tonnes/ha that decrease towards a plateau of 0.67 for yields of 15 tonnes/ha, see Figure 4. The mean of all measurements is 0,783 and corresponds to a yield of about 10 tonnes/ha. Unfortunately, no trend line was plotted.

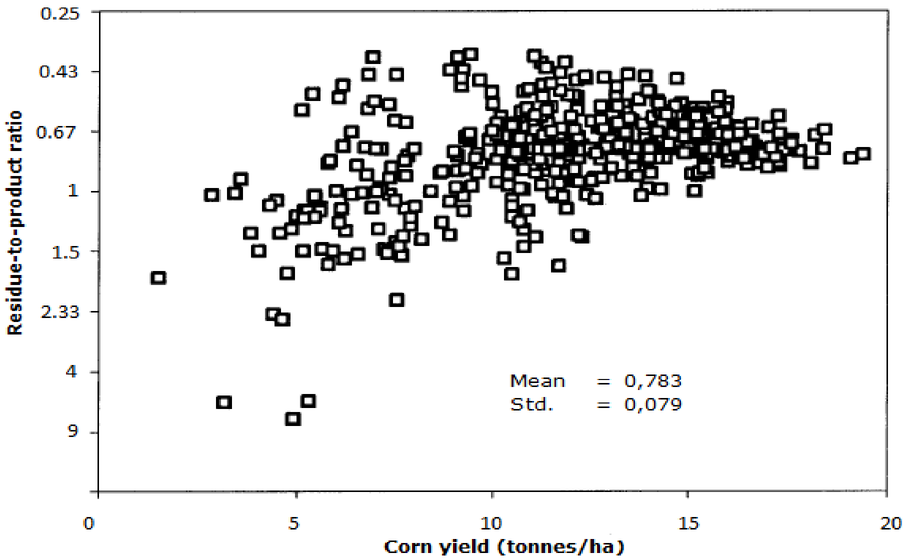

Figure 4: Residue-to-product ratio as a function of dry matter yield for different tillage and residue removal practices, adapted from {{128 Linden, D.R. 2000}}. In the original graph the harvest index (crop yield/total above ground biomass) is plotted as a function of yield in bu/acre, the unit conversion causes the seemingly odd scales on the axes.

During a presentation on sustainable maize harvests at the bioenergy feedstock symposium in Illinois Mike Edgerton discussed the relation between the residue-to-product ratio and the yield (Edgerton 2011). During two growing seasons the maize (grain) and residue yields were measured, see Figure 5. The graph indicates a relation similar to the relation suggested by the studies by Scarlat (Scarlat, Blujdea & Dallemand 2011b) and Linden (Linden, Clapp & Dowdy 2000).

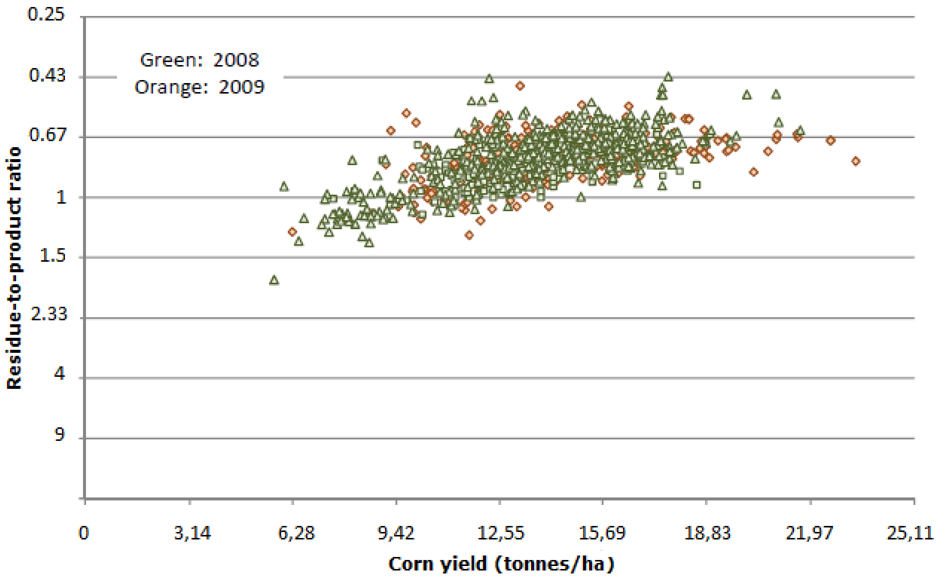

Figure 5: Residue-to-product ratio as a function of crop yield, adapted from (Edgerton 2011). The original picture showed the harvest index (crop yield/total above ground biomass) as a function of the yield (Bu/acre), the unit conversion causes the odd axis scales.

During the expert consultation 'cereals straw resources for bioenergy in the European Union' Edwards et al. (Edwards et al. 2006) showed that the RPR for wheat varied according to the yield. For yields as low as 1 tonne/ha the ratio was said to be 1 and for yields of 10 tonnes/ha the ratio was 0.6. In between the graph had a asymptotic shape and for a yield of 5 tonnes/ha the RPR was about 0.88.

5.1.1.2 **Other factors affecting the RPR**

Besides by the crop yield the RPR is also affected by the particular climate conditions, mostly water availability and temperature, during a growing season(Nel 2011). The RPR of wheat is also dependent on the season in which the crop is grown, i.e. whether it's winter or spring wheat (Patterson et al. 1995). If a plant experiences stress such as water scarcity due to draught, this affects the RPR. For instance if these stresses are experienced during the first half of the growing season, the plant spends relatively more energy on producing seeds and less on producing non-seed plant material in the second half of the growing season (Nel 2011). Furthermore the RPR varies for the different varieties cultivated.

5.1.1.2.1 ***Discussion and conclusion RPR for maize and wheat***

From the above it can be concluded that the residue-to-product ratio is not a constant factor, it is affected by both the yield and the extent to which crops experience stress during growth. The fact that the RPR is not only dependent on the yield explains why the R^2 values of the trend lines in Figure 3, Figure 4 and Figure 5.

Since annual climate variations causing plant stress are unpredictable, only the dependence of the RPR on crop yield is accounted for in this study. Table 3 provides a comparison of the RPR's for different yields as presented in the studies discussed in section 5.1.1, the study by Fisher et al. (Fischer et al. 2007) is excluded because it is based on data from 1979 to 1991, as mentioned. The crop varieties currently cultivated differ distinctly form those cultivated during the considered period. The crop varieties have been selected or even genetically designed to produce more edible biomass and less residual biomass.

Throughout this study, the relation as defined by Scarlat et al. (Scarlat, Blujdea & Dallemand 2011b) is used. This study is based on an extensive reference base that covers various countries and the equations seem to describe the variation in RPR realistically. Considering maize the difference between the RPR for the low and high yields is less than it is in the other two studies (see Table 3), these more conservative estimates are justified since the yield is not the only factor affecting the RPR. With regard to wheat the relation given by Scarlat seems to be more realistic considering the fact that in general the RPR is assumed to be 1.3 tonnes/ha (Kim, Dale 2004, Jingura, Matengaifa 2008, Scarlat, Blujdea & Dallemand 2011b).

Using these equations it is important to keep in mind that the R^2 values are low (0.17 for maize and 0.29 for wheat), indicating that the relation between the crop yield and the RPR is rather weak.

crop yield (t/ha) Maize	1,00	5,00	10,00	15,00	20,00	Reference
RPR	1,34	1,05	0,92	0,85	0,80	Sarlat et al. 2011
RPR	-	1,50	0,79	0,67	0,80	Linden et al. 2000
RPR	-	1,20	1,00	0,75	0,65	Edgerton 2011
Wheat						
RPR	1,50	0,99	0,77	0,64	-	Sarlat et al. 2011
RPR	0,94	0,88	0,62	-	-	EC JRC, 2006

Table 3: Comparison between maize and wheat RPR's for the discussed studies.

5.1.2 Sugar cane

Since sugar production produces to separate residue streams, first the harvest residues (tops and trash) and thereafter the process residues (bagasse) are discussed.

5.1.2.1 Tops and trash

5.1.2.1.1 *Relation between RPR and yield*

The amount of sugar cane tops and trash (including green and dry leaves) depends to some extend on the sugar cane variety, crop age at harvest, climatic conditions, topping height and soil type (Macedo, Leal & Hassuani 2001). Table 4 presents the average results of a study by Macedo (2001) who measured the division of biomass between the harvestable stalk and the tops and trash for the three most extensively planted cane varieties in two different regions in Brazil, at different stages of cut during two growing seasons.

Variety	Stage of cut	Productivity in stalks (t/ha)	Dry tops & trash (t/ha)	RPR
SP79-1011	1st	120,0	17,8	0,15
	3rd	91,5	15,0	0,16
	5th	84,2	13,7	0,16
SP80-1842	1st	135,8	14,6	0,11
	3rd	100,5	12,6	0,13
	5th	91,6	10,5	0,11
RB72454	1st	134,3	17,2	0,13
	3rd	99,8	14,9	0,15
	5th	78,2	13,6	0,17
Average		104,0	14,4	0,14

Table 4: RPR's for sugar cane tops and trash, adapted from{{144 Macedo, I.C. 2001}}.

In 2005, Hassuani et al. published a book on power production from sugar cane bagasse and trash which contained a review of studies that measured the trash production of different sugar cane varieties, see Table 5.

Variety	Productivity in Stalks (t/ha)	Dry tops & trash (t/ha)	RPR
NA56-79	72,5	13,3	0,18
SP70-1143	70	11,7	0,17
SP70-1143	88,3	11,0	0,12
SP70-1284	77,2	7,4	0,10
RB72454	83,1	19,0	0,23
SP71-1406	75,6	14,4	0,19
SP71-1406	68,6	13,5	0,20
SP71-6163	79,5	14,2	0,18
SP71-6163	74,9	11,7	0,16
SP71-6163	82,5	24,3	0,30
Average	**77,2**	**14,1**	**0,18**

Table 5: RPR's for sugar cane tops and trash, adapted from (Hassuani, Leal & Macedo 2005)

Figure 6 shows the relation between the RPR and the cane yield based on the combined data from Table 4 and Table 5. The trend line is described by Equation 14.

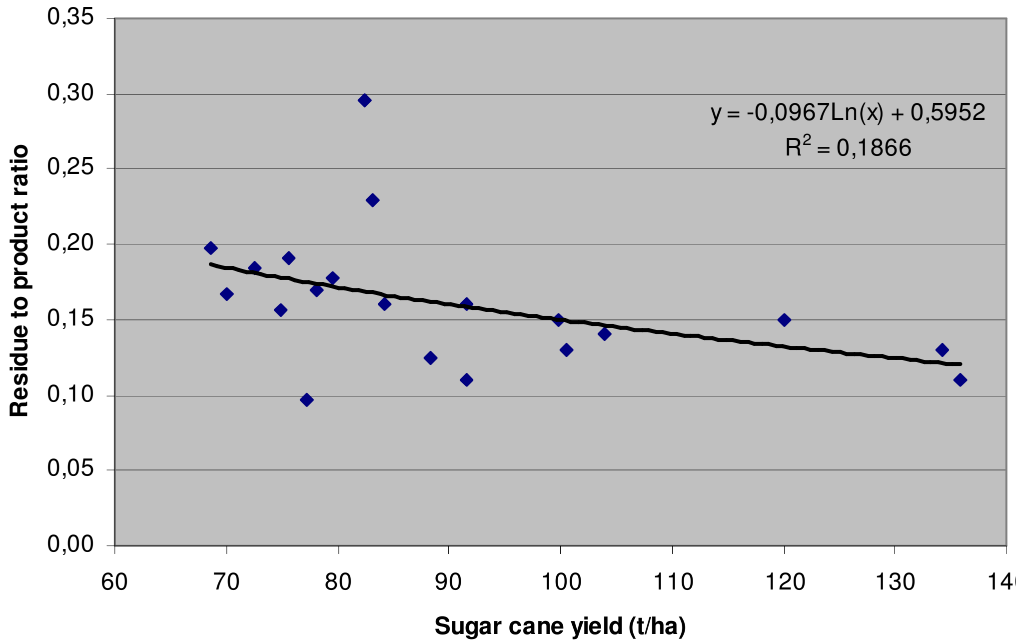

Figure 6: Residue to product ratio as a function of cane yield.

$$RPR_{Sugar\,cane\,tops\,\&\,trash} = -0{,}097 * \ln(yield) + 0{,}560\ ; \qquad R^2=0.19$$

Equation 14: Relation between the residue to product ratio and the sugar cane yield (tonne/ha) for sugar cane tops and trash.

5.1.2.1.2 *Other factors affecting the RPR*

Similar to the RPR for maize and wheat, the RPR is not solely dependent on the sugar cane yield. The amount of sugar cane tops and trash depends to some extend on the sugar cane variety, crop age at harvest, climatic conditions, topping height and soil type (Macedo, Leal & Hassuani 2001). For a discussion on the influences stress can have on crop growth, see section Other factors affecting the RPR 5.1.1.2.

5.1.2.1.3 *Discussion and conclusion sugar cane tops and trash*

The R^2 value (0.19) of the trend line in Figure 6 indicates that the relation between the RPR for tops and trash and the cane yield is rather weak, similar to the relation between the RPR for maize and wheat and their respective crop yields. Again, this can be explained by the fact that the RPR is also dependent on other factors as described above.

Since the factors other than the yield that influence the RPR for sugar cane tops and trash can realistically not be taken into account, only the dependence on the crop yield is considered. Therefore, the relation described by Equation 12 is used.

5.1.2.2 **Sugar cane bagasse**

The amount of bagasse produced per tonne of cane stalks pressed might vary for the different cane varieties and pressing techniques used. Unfortunately, the required data to determine whether such a relation exists is lacking and therefore an average RPR for bagasse will be assumed. The RPR is typically assumed to range between 0.25 and 0.33 with an average of 0.29 (Euler 2010, Hiloidhari, Baruah 2011a, Purohit 2009).

5.1.3 Conclusion residue to product ratio

As concluded in section 5.1.1.2.1 and 5.1.2.1.3, the dependence of the RPR on the crop yield is best described by the equations summarized in Table 6. Furthermore, the ratio for sugar cane bagasse is assumed to be constant since there is no data available on how it varies under different circumstances, e.g. cane pressing techniques.

Resiude type	**RPR**
Maize harvest residues	-0,18 *ln(Y)+1,34
Wheat harvest residues	-0,32*ln(Y)+1,50
Sugar cane tops and trash	-0,097*ln(Y)+0,60
Sugar cane bagasse	0,29

Table 6: The RPR’s as used in this study. Y: yield in tonne/ha.

5.2 Higher heating value

The higher heating value of the harvesting residues depends mainly on the ash content of the biomass (Jenkins, Bakker & Wei 1996).This in turn depends on the composition of the biomass, the more woody material the mixture contains the lower the ash content and the higher the HHV. Although there is some variation in the lower heating value for a certain residue type, the variation mainly occurs between different types of residues therefore this study assumes a constant HHV for each residue type.

The HHV of the residues was calculated based on the ECN Phyllis database for biomass and waste (Energy Research Centre of the Netherlands 2011) and the biomass feedstock composition and property database (US department of energy 2004). Both data bases contain original data obtained from analysis of residue samples and thus provide a solid reference. The averages of the data form both databases were used to calculate the overall average. Neither of these databases provided data on sugar cane harvest residues so another reference was used. The results are presented in Table 7.

Residue type	HHV_{dry}(GJ/t)	Reference
Maize harvest residues	18,1	ECN phyllis database
	18,3	Biomass feedstock composition and property database, US dep. of agriculture
avergae	**18,2**	
Wheat harvest residudes	18,2	ECN phyllis database
	17,4	Biomass feedstock composition and property database, US dep. of agriculture
avergae	**17,8**	
Sugar cane harvest residues	**16,5**	Macedo et al. 2001
Sugar cane bagasse	18,8	ECN phyllis database
	19,1	Biomass feedstock composition and property database, US dep. of agriculture
avergae	**19,0**	

Table 7: Higher heating values (GJ/$tonne_{dry}$) for different residue types (dry basis).

5.3 Moisture content

The moisture content of the harvest residues depends on the time of residue harvest. In arid climates, farmers leave the cereals in the field to dry and will only harvest when the crop is dry. In this study, the moisture content of the residues will be regarded as a constant factor as measured when the crop has reached maturity. Table 8, Table 9, Table 10, Table 11 provide an overview of the values used in relevant literature for maize residues, wheat residues, sugar cane tops and leaves and sugar cane bagasse respectively, and the averages thereof that are used throughout this study.

Moisture content (%)	Reference
30	Scarlat et al. 2011
11,5	Holoidhari et al. 2011
21,5	Kim et al. 2004
20	Euler 2010
11,5-22	Koopmans et al. 2008
15-30	Cosic et al. 2011
15	Fisher et al. 2010
11,5	Singh et al. 2008
15	IEA 2010
19,01	**Average**

Table 8: Moisture content of Maize residues

Moisture content (%)	Reference
15	Koopmans et al. 2008
15	Fisher et al. 2010
9,2	Singh et al 2008
15	Scarlat et al. 2011
9,9	Kim et al. 2004
15	IEA 2010
13	**Average**

Table 9: Moisture content of wheat residues

Moisture content (%)	Reference
74	Kim et al. 2004
59,2	Singh et al. 2008
59,2	Holoidhari et al. 2011
75	IEA 2010
65,6	Hassuani et al. 2005
67	**Average**

Table 10: Moisture content of sugar cane tops and leaves

Moisture content (%)	Reference
46	Turn et al. 2006
50	Macedo et al. 2004
50	Euler 2010
55	ECN Phyllis database
50	Hassuani et al. 2005
50	**Average**

Table 11: Moisture content of sugar cane bagasse

5.4 Conclusion theoretical potential

A relation between the crop yield and the RPR was determined for all residues types except for bagasse (due to lacking data). It is concluded that besides by the yield the RPR is also affected by other factors such as plant stresses experienced during growth caused by annual climatic variations and specific crop variety grown. Because of this interdependence, only part of the variability of the RPR can be explained by the yield and therefore it is stressed that these relations must be used with caution.

Furthermore, averages of the HHV_{dry} and the moisture content were calculated from literature. For both factors it was not possible to explain the variance by a dependence on a variable. Table 12 presents an overview of the results and thus of the values as used throughout this study.

Residue type	**RPR**	**HHV_{dry}(GJ/t)**	**MC (%)**
Maize harvest residues	-0.1807 *ln(yield (t/ha))+1.3373	18,2	19
Wheat harvest residues	-0.3186*ln(yield (t/ha))+1.503	17,8	13
Sugar cane harvest residues	-0,097*ln(yield(t/ha))+0,5952	16,7	67
Sugar cane bagasse	0,29	19,0	50

Table 12: Overview of the factors required to calculate the theoretical potential.

6 Factors influencing the sustainable and technical potential

As defined in section 4.5.2 the technical potential is the fraction of the theoretical potential that can be produced *sustainably* given the level of technical advancement, not limited by competing uses of residues. As the definition indicates, two factors are of importance here: the amount of residues that can be removed sustainably and the amount of residues required for competing uses (see section 4.5.2.1 and 4.5.2.2).

This chapter discusses the relevant literature, firstly to see whether there is consensus on how much of much of the produced residues can be removed sustainably and, secondly, to assess the demand for residues by other uses than energy production. The focus hereby is on the methods used for calculating both limiting factors.

6.1 Sustainable potential

6.1.1 Effects of residue removal

Before looking into the amount of residues which can potentially be removed, it is good to get a clear picture of what the effects of removing residue from the field are in general.

The most interesting study is done by Blanco-Canqui et al. (Blanco-Canqui, Lal 2007) who measured the soil and crop response to maize stover removal. The study was conducted in Ohio on land used for continuous maize production and under no-till management. The results show that removal of more than 25% of the produced stover decreased soil organic carbon stocks and reduced soil productivity. In the worst case, stover removal exceeding 50% reduced maize yields by 1.94 tonne/ha and decreased SOC levels by 1.63 tonne/ha. This was for sloping soils prone to erosion. The extent of the negative effects was depend on the soil type and slope.

Besides the decline in SOC, the decreased yield can be explained by the decreased water infiltration when stover removal exceeded 25% and, reduction in plant available water and earthworm population when removal exceeded 50%. However, it is important to note that the effects were not significant for all soils.

The study concludes that SOC levels, water infiltration and temperature regimes in the top soil are negatively affected by stover removal. The magnitude of the impacts depend on soil type and slope. For erosion prone, sloping soils, less than 25% may be removed without negatively affecting soil heath and crop production. The authors stress the need to develop site-specific threshold levels for stover removal.

6.1.1.1 The function of residues in agricultural production systems

The positive and negative effects of a residue cover can be summarize as follows. The positive results are predominant, and given below (Wilhelm et al. 2004, Blanco-Canqui, Lal 2007, Andrews 2006, Lal 2008):

1. *Soil erosion*. The presence of a residue cover protects the soil from water as well as wind erosion.

2. *Soil organic matter/carbon:* Long term cultivation of land decreases the amount of soil organic matter present in the soil (Reicosky et al. 1995). The amount of soil organic matter can be maintained or even increased by leaving resiudes (both above and below ground) in the field. Moreover, residue removal rates that increase erosion as well as runoff, greatly decreases SOM and nutrient availability.

3. *Soil organisms*. The presence of residues positively effects soil quality indicators such as soil carbon, microbial activity, fungal biomass and earthworm populations, denoting good soil function and quality.

4. *Improved water infiltration*. Residues also improve the physical properties of the soil. Such as reduced bulk density and improved water infiltration. Without a residue cover the impact raindrops can lead to the formation of a crust which causes water runoff, in particular on sandy soils. When residues are present on the soil, they absorb most of the impact thereby greatly improving the infiltration.

5. *Drought resistance*. Soils covered with residue have reduced evaporation rates, thereby increasing the number of days crops can survive in drought conditions.

However, the effects of residues are not all positive. Especially in cooler climates residues can have negative effects (Mann, Tolbert & Cushman 2002).

1. *Poor crop establishment/early development.* Residues slow the warming of the soil in spring which can cause poor seed germination and thus have a negatively impact crop yields. Besides it can be hard for germinating crops, to 'break through' the residue cover. The emergence of seedlings can be improved by clearing the planting strips just before sowing.

2. *Risk of pests and diseases*. Leaving residues on the soil can increase the risk of pest and diseases, especially if crops are not rotated, since pathogens tend to survive in infested residues.

6.1.2 Overview of relevant studies

Now it has become clear that residues fulfil a vital function and cannot be removed to their full extent, the next step is to assess to what extent residues can be removed. Typically the amount of residues that can be removed sustainably is expressed as a percentage of the residues produced, called the sustainable removable fraction. Since generally the same values are used for all harvest residues assessed in this study they are discussed together in this section. Table 13 provides an overview of the values found in literature for the SRF and the percentage of the residues used for competing uses.

SRF (%)	Competing uses (%)	Region	Comments	Reference
25[a]	Included in SRF	World	The same SRF is assumed for all residue types	Smeets et al. 2006
25[e]	-	USA	Maize stover only; study accounts for different soil types,and slopes	Blanco-Canqui 2007
40[c]	6	World	Competing uses based on US data	Kim et al. 2004
13 - 70[a]	-	South Africa	Study stresses that the SRF needs to be determined for SA	Lynd et al. 2003
50[a]	Included in SRF	Europe		de Wit et al 2010
50[a]	-	USA	Study only considers maize	NETL 2007
40 - 50[a]	-	Romania	SRF of 40% for wheat and 50% for maize	Scarlat et al. 2011
50[a]	included in SRF	Europe	linear relationship between yield and RPR assumed	Fisher et al. 2010
40 - 70[c]	0,5-1 t/cattle	Croatia	0,5-1 t/head of cattle for livestock production	Cosic et al. 2011
70[a]	5	South Africa	% used for other applications based on US data	Euler 2010
80[a]	Included in SRF	India		Holoidhari et al. 2011
1,60 (t/ha)[c]		USA	SRF in tonnes/ha concerning maize stover and wheat straw	USDA 2003
Various[c]	-	USA	Values not speicified, calculation based on soil erosion control only	Nelson et al. 2004
-	15[a]	India	10% lost in collection, transport and storage	Purohit 2009
-	24 - 80	India	maize: 24%; bagasse: 45%; tops and trash: 60%; straw: 80%	Singh et al. 2008

Table 13: Values used in literature for the sustainable removable fraction and percentage used for competing uses.
[a] Value is assumed by authors
[c] Value is calculated by authors
[e] Value is experimentally determined by authors

A few important conclusions can be drawn based on Table 13. Firstly, the variation in SRF is huge ranging from 25% to 80%. Secondly, most studies assume a SRF, often without much reasoning. The combination of these two conclusions makes it impossible to make a good comparison between the values, looking for factors that can explain the observed differences. The discussion below therefore only assess the studies that calculated a SRF or determined it experimentally. Hereby it is noted that no studies that look into the technical potential for sugar cane tops and trash could be found.

6.1.2.1 Discussion of methodologies to calculate the sustainable removable amount of residues

All the articles from Table 13 that actually calculate a potential follow roughly the same methodology, they calculate the required soil cover to protect it from wind and water erosion. The necessary residue input to remain healthy soil organic carbon levels are not taken into account.

Gallagher et al. (Gallagher et al. 2003) base their calculations on the 30% required soil cover, required by the 'National Resource Conservation Service'. Kim et al. (Kim, Dale 2004) depart from this same 30% but double it to 60% due to uncertainties about the local conditions. Ćosić et al. (Cosic, Stanic & Duic 2011) present a necessary soil cover of 1.0-2.0tonne/ha to protect against wind erosion and a 0.5tonne/ha-continuous cover to protect against rain erosion with regard to wheat straw. For maize stover, 30% of the produced stover is said to be enough to protect the soil. Nelson et al. (Nelson et al. 2004) present a methodology to calculate the required soil cover to protect the soil against wind erosion, using the 'wind erosion equation'(WEQ), and against rainfall erosion, using the 'revised universal soil loss equation (RULSE).

The 30% soil cover is subject of debate and many argue that it is too low. Therefore, the next section will look in detail at the prevention of soil erosion by means of a residue cover.

6.1.2.1.1 *Prevention of soil erosion*

Erosion is recognized as a worldwide problem. Depending on the soil type even small losses through erosion can have a significant adverse effect on the quality of the soil as it can increase the erosion rates above the natural rate of soil formation (Nelson 2002). For protection against erosion the soil should be covered with residues or, even better, vegetation(Ministry of Agriculture and Food, British Columbia, Canada 2000). The interesting question is, how large should the residue cover be, this is discussed below.

6.1.2.1.2 ***Required soil cover***

Figure 7 shows the soil loss relative to the soil loss without a residue cover as a function of the residue cover for two different regions in the USA. The relative soil loss is defined as the soil loss of an area with a cover relative to an area of bare soil. It can be concluded that even in the least favourable scenario a residue cover of 65% - 70% reduces the soil loss to 10% in the case of water erosion and 40%-45% would do the same for wind erosion, see Figure 7 and Figure 8. Figure 9 shows that a residue cover of 70% would require roughly 2 tonnes residues/hectare.

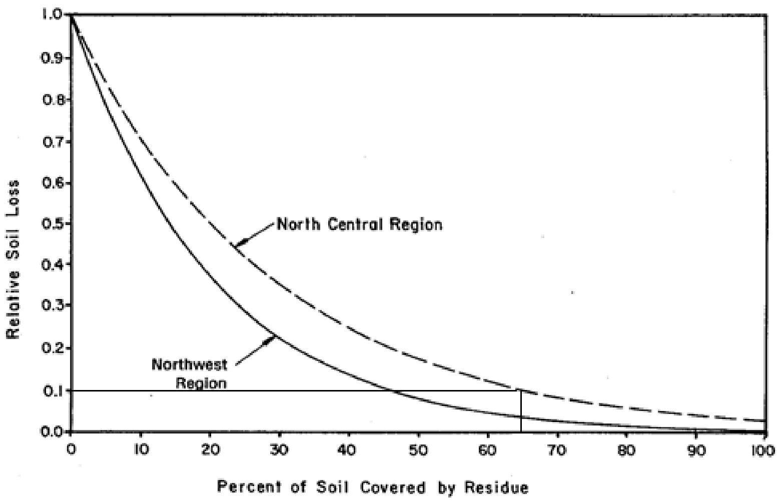

Figure 7: Relation between the relative soil loss as an effect of water erosion and the percentage of the soil covered by residues. Results are shown for two different regions in the USA. Adapted from Papendick et al. (Papendick, Moldenhauer 1995).

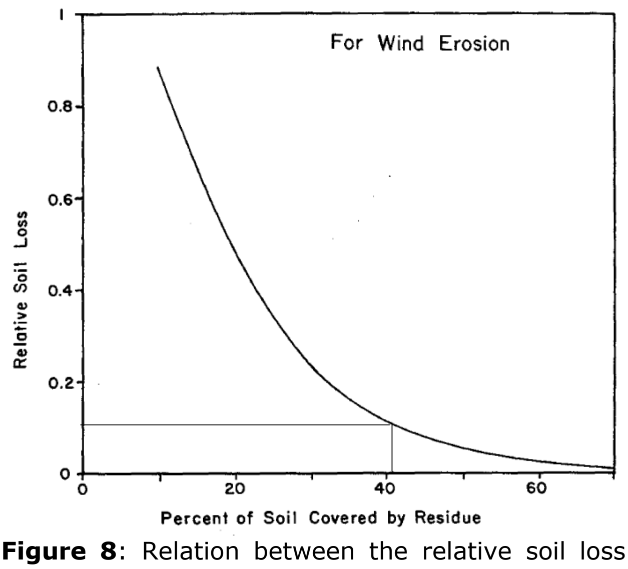

Figure 8: Relation between the relative soil loss as an effect of wind erosion and the percentage of the soil covered by residues. Adapted from Papendick et al. (Papendick, Moldenhauer 1995).

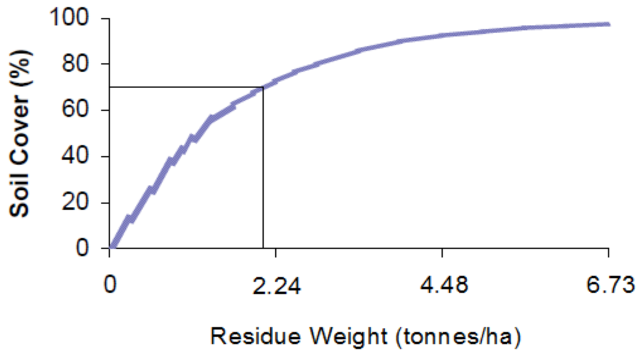

Figure 9: The exponential relation between the percentage of soil covered by residues and the residue weight per hectare for common small grains and annual legumes. Adapted from Andrews (Andrews 2006).

In line with the results presented in Figure 7, Andrews (Andrews 2006) show that leaving more than 2 tonnes residues per ha only gas a very limited effect in reducing runoff and the resulting soil loss under no-till conditions, see Figure 10.

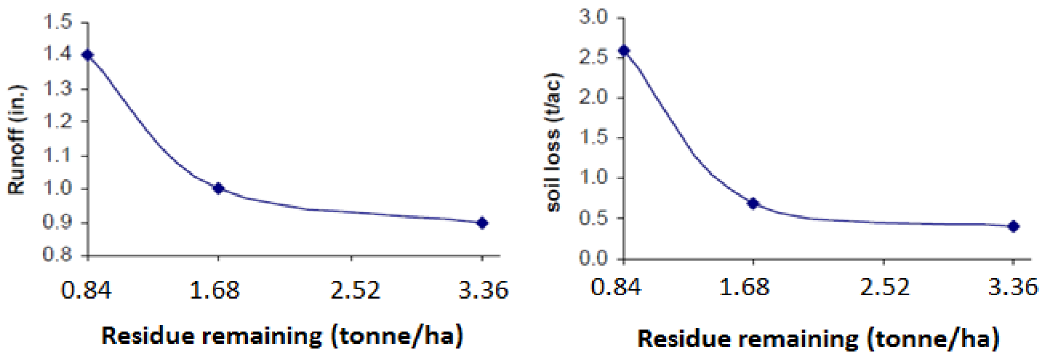

Figure 10: Runoff and soil loss as a function of residue cover under no-till conditions (Andrews 2006).

6.1.2.1.3 *The importance of no-till*

When residues are left in the field for erosion protection, it is important that these residues are not incorporated in the soil by tillage as this reduces protection. This effect is shown in Figure 10. Furthermore, Andrews (Andrews 2006) stresses the importance of tillage-residue interaction when looking into the protection against erosion. No-till without a residue cover can allow for more soil erosion than conventional tillage whereas no-till combined with a residue cover generally results in less erosion than conventional tillage.

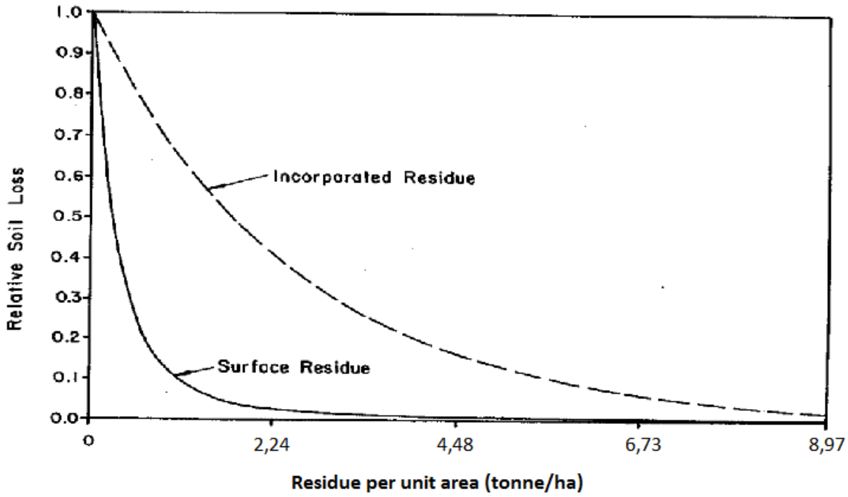

Figure 11: The difference in protection between surface residues and incorporated residues. Adapted from (Papendick, Moldenhauer 1995).

6.1.3 Conclusion and discussion

6.1.3.1 Required soil cover for erosion control

From the above it can be concluded that a soil cover of about 70% or 2 tonnes residues per hectare is enough to protect the soil against wind and water erosion. Leaving larger quantities of residues on the field reduces erosion only marginally. This study therefore uses the 2 tonnes/ha cover needed to protect the soil from erosion as the minimum amount of residues that should be left in the field after harvest. Hereby it is stressed that is should be combined with no-till management.

This value will be treated as a constant factor although the required cover might be higher for sloped lands an or in areas prone to severe storms with high winds and intense rain. The inclusion of such factors is beyond the scope of this thesis. For calculating site specific required residue covers, the methodology presented by Nelson (Nelson et al. 2004) is usefull but requires detailed input data (e.g. erodibility index, ridge roughness factor, climate factor etc.).

6.1.3.2 Soil organic carbon

However, looking back at section 6.1.1.1, the prevention of erosion is only one of the functions of agricultural residues. It is true that a residue cover which prevents erosion also improves water infiltration and increases drought resistance, two other benefits of leaving residues in the field. But, this still leaves two functions unaccounted for, maintaining SOC levels and stimulating the presence of (micro)organisms.

It is safe to assume that if organic carbon levels are sufficient, there will also be a healthy amount of (micro)organisms since they feed on the organic material. SOC is a crucial soil quality parameter, as it is positively linked to most desirable soil quality characteristics and has a positive effect on soil and crop productivity(Wilhelm et al. 2004, Reicosky et al. 1995). Nonetheless, information on the required amount of residues needed in order to maintain healthy soil organic carbon levels are lacking.

Wilhelm et al. (Wilhelm et al. 2004) therefore urge the development of a tool capable of determining site specific maximum permissible removal rates. Since Lynd et al. (Lynd et al. 2003) stress the need for such a tool for South Africa, the second part of this thesis tries to develop a simple tool capable of determining residue inputs to maintain healthy SOC levels under different conditions, see chapter 9.

6.2 Demand for residues by competing uses

In the literature values ranging from 0% to 100% can be found for the non-energy uses of residues depending on the type of residues and the region studied. Kadam and McMillan (Kadam, McMillan 2003) estimate that in the US, no more than 5% of the maize stover is used for off farm field use. While the IEA (IEA 2010) estimates that in some countries up to 90% maize stover is used for non-energy uses. This section tries to explain the differences between the fractions of the residues used for non-energy purposes.

As mentioned in section 4.5.2.2 the current uses of crop residues can be divided into three main categories: animal uses, biobased materials and other uses. The fraction of residues used for biobased materials and other uses is too small to be considered here and therefore the demand for residues will be calculated based on the requirements of the livestock population.

6.2.1 Animal uses

Wheat and maize residues are commonly used for animal bedding and feed during the winter time when the cattle are kept indoors(Cosic, Stanic & Duic 2011). Sugar cane residues are not used for animal bedding or feed and thus will not be considered in this section.

6.2.1.1 Maize residues

Maize stover can be used as animal feed during the winter period when the cattle cannot graze on the pastures. This implies that the amount of residues required depends on the size of the livestock population in a certain area and the length of the grazing season (Gallagher et al. 2003). Maize stover is a low quality feed because it is devoid of vitamins and low in protein, since its physical character also makes it unattractive for cattle it can only make up as much as 20% to 30% of their dry matter feed requirement (Kadam, McMillan 2003, Adams 1998, Samples, McCutcheon 2002). At last, not the entire livestock population feeds on residues as this is typically only the case in areas where maize is grown(Crichton, Gertenbach & van Henning 1998b). From the above it can be concluded that the annual requirement of maize stover for animal feed can be calculated according to
Equation **15**.

$$Yearly maize stover requirement = (365 - G) * 0.25 * P * F * C$$

Equation 15: Calculation of the yearly maize stover requirement for animal feed in a certain region.

Where:
- G: the number of days in an average grazing season
- P: Percentage of the livestock population feeding on residues.

Type	Feed requirement (kg/day)
Beef cows	12,5
Milk cows	11,4

Table 14: Daily feed requirement for cattle{{178 Gallagher, P. 2003}}.

- F: the Daily feed requirement of cattle in tones.
-C: Heads of cattle present.

The daily feed requirements for different types of cattle are shown in Table 14. Alternatively the average value of 12 kg/day can be used since the values do not differ much.

6.2.1.2 **Wheat residues**

Wheat residues are primarily used as animal bedding since the feed value is too low. A large number of animals require bedding, but to avoid getting lost in too much detail this study only considers cattle, pigs and sheep as they are the largest consumers of straw.

Similar to the demand for feed, the demand for bedding depends on the number of livestock and the duration of the winter period, however the exact requirement for bedding is difficult to establish as it depends on the farming system (not all animals use bedding) and the local availability of straw(Scarlat, Blujdea & Dallemand 2011b). Some animals use bedding year round since they are always kept indoors while some only use bedding in winter as they graze outside during summer (bedding during winter can be provided both indoors or outdoors), and some animals will never use bedding. For simplicity, this study assumes all livestock require bedding but only do so during the winter period since they are allowed to graze outside as long as possible.

Cattle require the largest amount of bedding. Cosic et al. (Cosic, Stanic & Duic 2011) assume that the annual wheat straw consumption ranges between 0.5 and 1 tonne/head of cattle, in their case study of Croatia a consumption 0.6 tonne/head of cattle is used. Scarlat et al. (Scarlat, Blujdea & Dallemand 2011b) assume a consumption of 1.5kg of straw/day per head of cattle (which equals 0.55 tonne/year) in their study of Romania, thereby assuming that only a quarter of the cattle population uses bedding. Thus, a daily consumption of 1.5kg/head of cattle seems to be a good estimate.

Pigs and sheep also use straw for bedding although the quantities are much smaller. The annual use for sheep can be estimated at 0.37 tonne/head of sheep, based on a daily consumption of 1kg, and at 0.18 tonne/head of pig for pigs, based on a daily consumption of 0.5kg (Scarlat, Blujdea & Dallemand 2011b).

Not all the entire livestock population uses bedding, this depends on availability and type of farm. Summarizing, the annual requirement for wheat straw for animal bedding can be calculated using Equation 16.

$$Annual\ wheat\ straw\ requirement = \frac{(365 - GS) * \left(HOC * P * 1.5 + HOS * P * 1 + HOP * P * 0{,}5\right)}{1000}$$

Equation 16: Calculation of the annual wheat straw requirements (in tonnes) for animal bedding considering cattle, sheep and pigs.

Where:
- GS: Number of days in the average grazing season.
- P: Percentage of the livestock population using bedding.
- HOC: Head of cattle.
- HOS: Head of sheep.
- HOP: Head of pig.

6.2.2 Loss of tops and trash as an effect of burning

Driven by rising labor cost, and new insights on the beneficial effects of leaving sugar cane trash in the field there is a global shift from burnt cane harvesting towards green cane harvesting. Furthermore this shift is also due to public and environmental pressures against open field burning (Muir, Eggleston & Barker 2009). Leaving the sugar cane trash in the field can potentially increase cane yields due to the conservation of water, soil organic carbon and nitrogen (van Antwerpen et al. 2002). On the other hand, if the cane stalks are not cleaned properly, attached trash has a negative impact on sugar production (Muir, Eggleston & Barker 2009).

The percentage of sugar cane harvested after burning varies widely for different countries but it is not the aim of the thesis to calculate the average of different percentages as such an average has no value.

6.2.3 Discussion and conclusion

It is concluded that the demand for maize and wheat residues for animal uses can be calculated based on the demand for maize stover and wheat straw by animals and the size of the livestock population. This is done according to
Equation 15 and Equation 16.

6.3 Discussion and conclusion technical potential

Summarizing, a residue cover of 2 tonne/ha provides sufficient protection against wind and rainfall-induced erosion, a larger cover only results in a marginal further reduction. Besides erosion control, maintaining healthy soil organic carbon levels is of major concern. A model capable of determining required residue inputs under different local conditions needs to be developed.

With regard to the demand for residues by the livestock farmers, this can be calculated based on the size of the livestock population using
Equation 15 and Equation 16 as shown in section 6.2.1.

7 Residue cost at farm gate

The aim of this chapter is to get an idea of the residue cost ranges in different parts of the world, to provide a benchmark for the results from the case study for South Africa. The most data is available for the U.S. due to the large interest to use residues for bioenergy purposes. Note that this chapter doesn´t try to give a complete overview of all published articles on supply cost but rather assess a few comprehensive articles in order to establish cost ranges.

For maize and wheat supply cost, both the U.S. European cost are assessed, for sugar cane tops and trash the Brazilian cost are assessed. Since the bagasse is available at farm gate at zero cost, this is excluded from the analysis.

7.1 Direct and indirect residue supply cost

7.1.1 Cost in the U.S.A. - Maize and wheat

7.1.1.1 Results

Most articles in the U.S. focus on maize stover as this feedstock is the most abundant with an annual production of 196 Mtonne (Graham et al. 2007).

Different ways to produce bales
Three different ways of producing either maize stover or wheat straw bales are discussed in literature. All methods assume that first the maize/wheat itself is harvested using a combine harvester. The residues processed by the combine harvester (~30% for maize and ~50% for wheat) are blown out of the back of the combine and the rest of the residue is still anchored to the ground (Milhollin et al. 2011).

1. Shred, rake and bale (collection efficiency 80%): Because the residues are shredded and raked before baling, all the anchored residues can be baled additional to the material processed by the combine.
2. Rake and bale (collection efficiency 50%): Leaving out the shredding of the residue reduces collection efficiency by 20%.
3. Bale (collection efficiency 30%): In this scenario, the 'spreader on the combine harvester, normally used to evenly distribute the residues behind the combine, is switched of and therefore the combine drops the residues in a windrow.

Table 15 provides an overview of the values found in literature. It is hard to compare different studies as each study makes different assumptions and choices regarding to which cost are included. Since the energy market for maize stover and wheat straw is still in its infancy it is hard to determine the real price. The large differences in cost estimates for both stover and straw are due to regional cost differences, variations in yield and the collectable amount of residues, and the field operations included in collection.

Direct cost ($/tonne)	Included field operations[1]	Indirect cost[2] ($/tonne)	Total cost ($/tonne)	Total cost ($/GJ)	Reference
Maize stover cost					
7,3 - 7,7	Shred, bale, haul	7,9	15,2 - 15,6	0,84 - 0,86	Gallagher, 2003
14,9 - 17,9[3]	(Rake), bale, wrap	13,5	28,4 - 31,4	1,6 - 1,7	Milhollin, 2011
41,5 - 52,1	Bale, haul to CGP	12,5[4]	54,0 - 64,6	3,0 - 3,5	Perlack, 2002
4,0 - 8,5[5]	(Shred, rake) bale, wrap, haul	16,4	20,4 - 24,9	1,1 - 1,4	Brechbill, 2008
22,2 - 40,1[6]	(Shred, rake) bale, haul	7,8	30,0 - 47,9	1,6 - 2,6	Graham, 2007
Wheat straw cost					
13,1 - 30,4	Swat, bale, haul	6,1	19,2 - 36,5	1,1 - 2,1	Gallagher, 2003
35,0 - 38,5	Swat, bale, haul	12,9	47,9 - 51,4	2,7 - 2,9	Patterson, 1995

Table 15: Residue cost at farm gate (CFG) as presented by various studies**.** All cost are in 2011 U.S.$.

[1] Unless indicated otherwise, haul refers to hauling to the edge of the field.
[2] Defined as the nutrient replacement cost.
[3] Low cost include baling and wrapping (30% removal) and the high cost also include raking (50% removal).
[4] Assumed to also include farmer profit.
[5] Low cost for shredding, raking and baling on a 2000 acre farm, high cost for baling on a 500 acre farm.
[6] Low cost include shredding, raking and baling, high cost include only baling.

Single pass harvest methods

Atchinson and Hettenhaus (Atchinson, Hettenhaus 2003) assess the option to harvest maize stover in a more efficient manner. At the time, the study concluded that the only option is to harvest the entire crop (grain and residues) using a forage harvester and then separate the two products at the farm or a central point. He estimated that cost could decline to 30 $/tonne, delivered at a 50km radius. More recent research focused on single pass collection systems capable of separating the two harvest streams in the field.

Milhollin et al. (Milhollin et al. 2011) point out some interesting new collection methods under development but does not provide cost indications because most machinery is not commercially available yet. The single pass collection methods mentioned are:

1. Cob harvest only (collection efficiency: 15%): An attachment is added to the combine harvester which collects the maize cobs (after the kernels have been ripped off) in a cart.

2. Bale direct system (collection efficiency: 30%): Normally residues are blown out of the back of the combine harvester whereas in this system the residues exiting the baler are conveyed directly to a large baler, coupled to the combine harvester. In this way bales can be produced without the residues ever touching the field.

7.1.1.2 Discussion and conclusion

Cost ranges

From Table 15 it is concluded that the total cost to supply residues at farm gate in the U.S. vary from 15.2 $/tonne (0.84$/GJ) to 64.4 $/tonne (3.5$/GJ) for maize stover and wheat straw respectively. The variation in stover cost is mainly due to differences in the direct cost which vary from 4.0 $/tonne to 52.1 $/tonne, whereas the nutrient replacement cost are relatively constant 7.8 $/tonne 16.4 $/tonne. Regarding wheat straw the variation in direct cost, 13.1 $/tonne to 38.5 $/tonne is smaller and more or less equal to the variation in nutrient replacement cost, 19.2 $/tonne to 51.4 $/tonne. Finally, there are promising new developments aiming to harvest the crop and residue simultaneously, however costs of such methods are not known yet.

Relation between supply cost and the fraction of the residues harvested
It is interesting that in both the studies from Graham (Graham et al. 2007) and Brechbill (Brechbill, Tyner 2008) the residue supply cost decline when an increasing percentage of the residues is harvested, this is graphically represented in Figure 12. At first sight this seems contra intuitive as it requires more field operations to harvest a larger percentage of the available residues, which is expected to be more expensive. Apparently, the cost to harvest a hectare are fixed, this implies that the cost per tonne decline when more residues are collected from a hectare. It is questionable whether this is fully in line with reality as it can also be argued that the time required to e.g. bale a hectare is proportional to the amount of residues that must be baled.

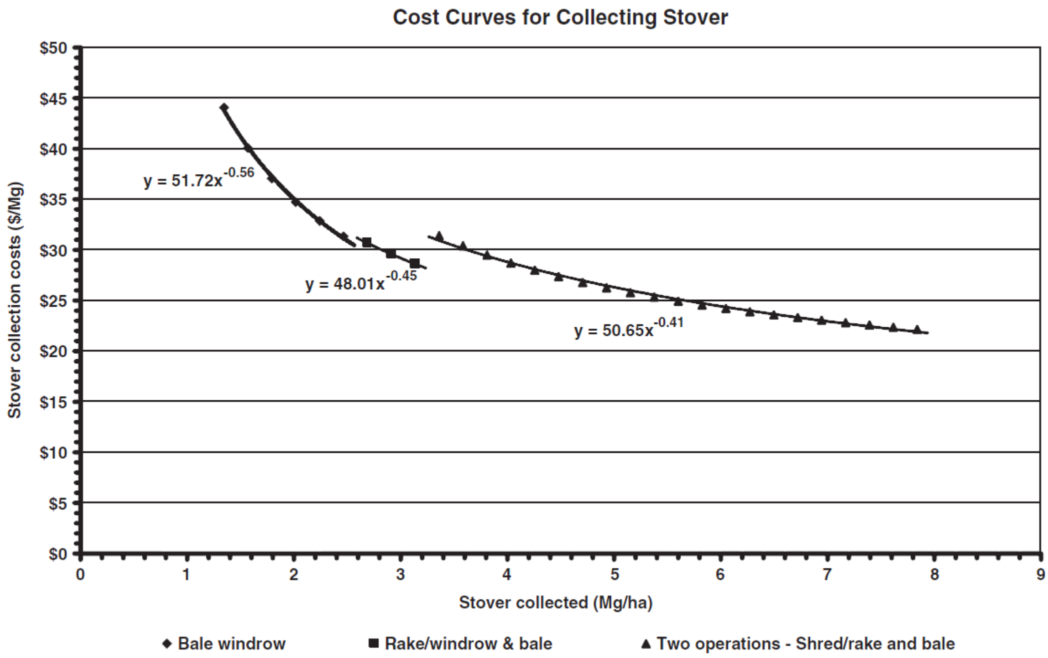

Figure 12: Maize stover collection cost as a function of the amount of residues removed per hectare. The total residue yield was 10 tonne/ha. Figure from (Graham et al. 2007).

7.1.2 Cost in Europe – Wheat

7.1.2.1 Results

Compared to the U.S. the data available on residue cost is limited. A comprehensive overview of the residue cost in the different European countries is given in an outlook to the contribution of bioenergy in the EU energy market in 2020 (Siemons et al. 2004). However, the cost in this study are the supply cost at factory gate and are taken as the opportunity cost in contrary to the U.S. cost which are based on a calculation of the direct and indirect cost for the farmer. The problem with this approach is that for many residues there is no market in the EU and furthermore the majority of the traded residues is usually traded informally, e.g. straw for animal feed or bedding (Siemons et al. 2004). The study only gives the supply cost at factory gate, since transport cost generally account for roughly 10% of the cost at factory gate, the cost at farm gate are assumed to be 90% of the cost at factory gate (Milhollin et al. 2011, Perlack, Turhollow 2002).

Country	Low cost estimate ($/tonne)	High cost estimate ($/tonne)	Average ($/tonne)	Average ($/GJ)
Austria	74,0	86,8	80,4	4,5
Germany	79,1	91,9	85,5	4,7
Danmark	76,5	102,1	89,3	5,0
Greece	30,6	127,6	79,1	4,4
Spain	28,1	43,4	35,7	2,0
Finland	35,7	84,2	60,0	3,3
France	91,9	99,5	95,7	5,3
Italy	28,1	71,4	49,8	2,8
Netherlands	71,4	127,6	99,5	5,5
Sweden	76,5	102,1	89,3	5,0
United Kingdom	40,8	71,4	56,1	3,1
Bulgaria	35,7	81,7	58,7	3,3
Czech Republic	-	-	38,3	2,1
Estonia	-	-	61,0	3,4
Hungary	-	-	40,8	2,3
Lithuania	-	-	58,7	3,3
Latvia	-	-	56,1	3,1
Poland	-	-	45,9	2,6
Romania	33,2	66,3	49,8	2,8
Slovakia	33,2	102,1	67,6	3,8
Slovenia	-	-	63,8	3,5
Average	**52,5**	**89,9**	**64,8**	**3,6**

Table 16: Supply cost ranges at farm gate in EU15+10+2 countries. The cost are an average for wheat (with ~60% the dominant residue type), maize, sunflower, rapeseed, olive trees and vines. It is assumed that the cost at farm gate equals 90% of the cost at factory gate. All values in 2010 U.S.$. Table adapted from (Siemons et al. 2004).

Since the data is unspecific, nothing is mentioned about exactly which cost are included and underlying assumptions and moreover not all the original references could be found, it is not possible to compare the differences between costs in different countries.

7.1.2.2 Discussion and conclusion

Although the data quality rather low and unspecific, it can be concluded from Table 16 that the average supply cost at farm gate for residues (mainly wheat straw) is 64.8 $/tonne or 3.6 $/GJ. The cost are the lowest in Romania, 33.2 $/tonne (1.84$/GJ), and the highest in Greece and the Netherlands 127.6 $/tonne (7.09$/GJ).

7.1.3 Cost in Brazil – Sugar cane

Sugar cane tops and trash are generally left in the field because sugar mills can generate the entire internal power demand of the sugar mill by burning bagasse and there is no market for the tops and trash. As a result, little data is available on the collection cost.

There are multiple ways for sugar cane trash harvest, as described by Hassuani et al. (Hassuani, Leal & Macedo 2005), all require unburned sugar cane harvest:

1. Trash baling (collection efficiency: 80%): During cane harvest, the stalks are cleaned by cleaning fans, blowing the trash back into the field. The trash can then be raked, baled and transported to the fields edge.

2. Simultaneous cane and trash harvest (collection efficiency 67%): During sugar cane harvest the cleaning fans are turned off, leaving the trash attached to the stalks. The cane and trash are then transported together to the sugar mill where they are separated in a dry cleaning station.
3. Simultaneous cane and trash harvest (collection efficiency 50%): This alternative is almost identical to the second harvest scenario but this time, only one of the two cleaning fans is turned collecting less trash with the cane.

The direct and indirect cost of harvesting trash according to these scenarios are depicted in Table 17.

Direct cost ($/tonne)	Harvest scenario	Indirect cost ($/tonne)	Total cost ($/tonne)	Total cost ($/GJ)	Reference
13,8	1	11,0	24,8	1,2	Macedo, 2001
11,1	1	6,5	17,5	1,06	Hassuani 2005
30,0	2	6,2	36,2	2,2	Hassuani 2005
7,4	3	7,5	14,9	0,90	Hassuani 2005

Table 17: Residue cost at factory gate since it is not possible to calculate the cost at farm gate when harvesting trash according to scenario 2 or 3. All cost in 2011 U.S.$

7.1.3.1 **Discussion and conclusion**

Cost ranges
From Table 17 it can be concluded that the cost for sugar cane trash at farm gate range from 14,9 $/tonne to 24.8 $/tonne equal to 0.9 $/GJ to 2.2 $/GJ. The direct cost range from 7.4 $/tonne to 30 $/tonne while the indirect cost range is smaller, from 6.2 $/tonne to 11 $/tonne.

Differences in cost
First of all the option harvest sugar cane trash according to scenario 2 is a promising option for cost-efficient sugar cane trash harvest. Then, it stands out that the direct cost for scenario 2 are about triple the cost of scenario 3 while the scenarios are much alike. This is explained by the fact that the cost for herbicide control under scenario 2 are almost double the cost in scenario 3 and the harvest cost for the cane are also higher. Since in scenario 3 all the trash is removed, there is no trash blanket left to prevent the grow of weeds, leading to high herbicide expenses.

7.2 Opportunity cost

The term opportunity cost is interpreted differently in literature. Some studies refer to the nutrient value of the residues as opportunity cost while others refer to the price of residues for cattle feed and or bedding as opportunity cost. In this study, the nutrients removed with the residues are regarded as indirect cost and the opportunity cost is the price paid for residues by competing uses.

First of all, it is hard to determine the true pice of residues or animal uses since the residues are typically traded informally (Siemons et al. 2004). The data available are shown in Table 18. No data on sugar cane trash was found, the opportunity cost are therefore assumed to be similar to the opportunity cost of maize stover.

Type	Opportunity cost ($/tonne)	Reference
Maize stover	51,3	Gallagher, 2003
Wheat straw	26,0	Gallagher, 2003
SC Bagasse	7,7	Gallagher, 2003
SC Trash[1]	51,3	

Table 18: Opportunity cost (cattle feed value) for different residue types, all prices in 2011 U.S.$.
[1] Assumed to be similar to the opportunity cost for maize stover.

The price paid for maize stover is the highest, simply because it contains more nutrients (e.g. sugar) than wheat straw or bagasse.

7.3 Discussion and conclusion

Data on cost at farm gate as well as opportunity cost discussed in this chapter are summarized in Table 19. It is concluded that sugar cane trash is available at the lowest cost whereas wheat straw is the most expensive feedstock considered. The cost of residues in Europe is twice as high as in the U.S., probably due to the large interest in using residues for energy purposes in the U.S. also triggering development of new, more cost-efficient, residues harvest methods. However, due to the low EU data quality the uncertainty is relatively high.

Type	Cost at farm gate				Opportunity cost
	Direct cost ($/tonne)	Indirect cost ($/tonne)	Total (average) ($/tonne)	Total (average) ($/GJ)	Average ($/tonne)
Maize stover (USA)	4,0 - 52,1	20,4 - 64,6	33,2	1,8	51,3
Wheat straw (USA)	13,1 - 38,5	6,1 - 12,9	38,8	2,2	26
Wheat straw (EU)	-	-	64,8	3,6	-
SG Bagasse (Brazil)	0	0	0	0	7,7[2]
SG Trash (Brazil)[1]	7,4 - 30	6,2 - 11	23,4	1,3	51,3[3]

Table 19: Summary residue cost at farm gate and opportunity cost for different residue types, all values in 2011 U.S.$.
[1] Cost at fatory gate instead of farm gate.
[2] U.S. cost
[3] Due to missing data, cost assumed to be equal to equal to the opportunity cost for maize stover.

New developments
In general, current (crop) harvest methods aim to harvest the main produce as efficient as possible, disregarding residues. This means residue harvest is inefficient and therefore there is much room for technical learning. There are promising new developments aiming to harvest the crop and residues in a single pass. For maize and wheat these developments are taking place in the U.S.A. but are still very new (some not even commercially available) so the costs are still unknown. For sugar cane these developments take place in Brazil, showed a possible total cost reduction of ~10 $/tonne compared to the average shown in Table 19.

Part 2: Case study for South Africa

The structure of this second part of the thesis is similar to the first part, discussing the theoretical potential, the technical potential and finally the supply cost for maize, wheat and sugar cane residues. The case study does not solely aim to calculate potentials but also to fill the gaps identified in the literature review by assessing which general conclusions can be drawn from the residue supply and cost in South Africa

8 Theoretical potential

8.1 Results

In order to calculate the theoretical potential for South Africa on a provincial level, the relations and values found in chapter 5 are used. When these data are combined with data on yield and production area, the theoretical potential for each crop can be calculated on a per hectare basis and in total according to Equation 1. Results are also presented on a mass basis. The results of shown in Table 20, Table 21, Table 22 and Table 23.

Province	Crop yield[1] (tonne/ha)	RPR[2] (tonne/tonne)	Moisture content[2]	HHV[2] (GJ/tonne$_{dry}$)	Potential (GJ/ha)	Production area[1] (kha)	Potential (PJ)	Potential (ktonne$_{dry}$)
Northern Cape	11,7	0,89	19%	18,2	153	49	7,59	417
Western Cape	9,4	0,93	19%	18,2	129	3	0,42	23
Eastern Cape	5,3	1,04	19%	18,2	81	15	1,26	69
KwaZulu-Natal	5,7	1,02	19%	18,2	85	77	6,59	362
Free State	4,0	1,09	19%	18,2	64	967	62,06	3.410
North West	3,2	1,13	19%	18,2	53	709	37,82	2.078
Gauteng	4,6	1,06	19%	18,2	72	101	7,29	401
Mpumalanga	5,1	1,04	19%	18,2	78	457	35,51	1.951
Limpopo	3,9	1,09	19%	18,2	63	45	2,79	153
Average[3]/total	4,2	1,07	19%	18,2	70	2.424	161,33	8.865

Table 20: Theoretical potential for bio-energy production from maize stover, calculated both in GJ/ha and in PJ (total) and in ktonne$_{dry}$(total) for South Africa.

[1] 5 year averages calculated from (South African Grain Information Service 2012).

[2] Values taken from or calculated with the formulas shown chapter 5.

[3] Averages are weighted averages.

Province	Crop yield[1] (tonne/ha)	RPR[2] (tonne/tonne)	Moisture content[2]	HHV[2] (GJ/tonne$_{dry}$)	Potential (GJ/ha)	Production area[1] (kha)	Potential (PJ)	Potential (ktonne$_{dry}$)
Northern Cape	6,4	0,91	13%	17,8	91	43	3,88	218
Western Cape	2,4	1,23	13%	17,8	45	306	13,80	775
Eastern Cape	3,8	1,08	13%	17,8	63	4	0,27	15
KwaZulu-Natal	4,9	1,00	13%	17,8	75	7	0,51	28
Free State	2,3	1,24	13%	17,8	44	259	11,28	633
North West	5,5	0,96	13%	17,8	82	24	1,99	112
Gauteng	6,1	0,92	13%	17,8	88	2	0,16	9
Mpumalanga	5,3	0,97	13%	17,8	80	8	0,64	36
Limpopo	5,2	0,97	13%	17,8	79	16	1,26	71
Average[3]/total	2,8	1,16	13%	17,8	55	669	33,78	1.898

Table 21: Theoretical potential for bioenergy production from wheat straw, calculated both in GJ/ha and in PJ (total) and in ktonne$_{dry}$(total) for South Africa.

[1] 5 year averages calculated from (South African Grain Information Service 2012).

[2] Values taken from or calculated with the formulas shown chapter 5.

[3] Averages are weighted averages.

Province	Crop yield[1] (tonne/ha)	RPR[3] (tonne/tonne)	Moisture content[3]	HHV[3] ($GJ/tonne_{dry}$)	Potential (GJ/ha)	Production area[1] (kha)	Potential (PJ)	Potential ($ktonne_{dry}$)
Northern Cape	-	-	-	-	0	0	0	0
Western Cape	-	-	-	-	0	0	0	0
Eastern Cape	-	-	-	-	0	0	0	0
KwaZulu-Natal[2]	60,9	0,20	67%	16,7	66	247	16,27	975
Free State	-	-	-	-	0	0	0	0
North West	-	-	-	-	0	0	0	0
Gauteng	-	-	-	-	0	0	0	0
Mpumalanga[2]	60,9	0,20	67%	16,7	66	62	4,07	244
Limpopo	-	-	-	-	0	0	0	0
Average[4]/total	60,94	0,20	67%	16,7	66	308	20,34	1.218

Table 22: Theoretical potential for bioenergy production from sugar cane tops and trash, calculated both in GJ/ha and in PJ (total) and in $ktonne_{dry}$(total) for South Africa.

[1] 5 year averages calculated from (based on FAOSTAT).

[2] Due to lacking data, the sugar cane yields in Kwa-Zulu Natal and Mpumalanga are assumed to be the same, this seems a fair assumption since the growing areas are close together and conditions are simialr. Furthermore, 80% of the production area is assumed to be located in KwaZulu-Natal and 20% in Mpumalanga (REF SA sugar industry directory http://www.sasa.org.za/files/Industry%20Directory%202011-2012.pdf)

[3] Values taken from or calculated with the formulas shown chapter 5.

[4] Averages are weighted averages.

Province	Crop yield[1] (tonne/ha)	RPR[3] (tonne/tonne)	Moisture content[3]	HHV[3] ($GJ/tonne_{dry}$)	Potential (GJ/ha)	Production area[1] (kha)	Potential (PJ)	Potential ($ktonne_{dry}$)
Northern Cape	-	-	-	-	0	0	0	0
Western Cape	-	-	-	-	0	0	0	0
Eastern Cape	-	-	-	-	0	0	0	0
KwaZulu-Natal[2]	60,9	0,29	50%	19,0	168	247	41,39	2.179
Free State	-	-	-	-	0	0	0	0
North West	-	-	-	-	0	0	0	0
Gauteng	-	-	-	-	0	0	0	0
Mpumalanga[2]	60,9	0,29	50%	19,0	168	62	10,35	545
Limpopo	-	-	-	-	0	0	0	0
Average[4]/total	60,94	0,29	50%	19,0	168	308	51,74	2.723

Table 23: Theoretical potential for bioenergy production from sugar cane bagasse, calculated both in GJ/ha and in PJ (total) and in $ktonne_{dry}$(total).

[1] 5 year averages calculated from (based on FAOSTAT) for South Africa.

[2] Due to lacking data, the sugar cane yields in Kwa-Zulu Natal and Mpumalanga are assumed to be the same, this seems a fair assumption since the growing areas are close together and conditions are simialr. Furthermore, 80% of the production area is assumed to be located in KwaZulu-Natal and 20% in Mpumalanga (REF SA sugar industry directory http://www.sasa.org.za/files/Industry%20Directory%202011-2012.pdf)

[3] Values taken from or calculated with the formulas shown chapter 5.

[4] Averages are weighted averages.

8.2 Conclusion and discussion

From Table 20, Table 21, Table 22 and Table 23 it can be seen that the total theoretical potential is 267 PJ, roughly 5% of South Africa's annual primary energy demand. Furthermore Figure 13 provides a comparison of the size of the different potentials. It is clear that the maize stover is potentially the best feedstock for bioenergy generation.

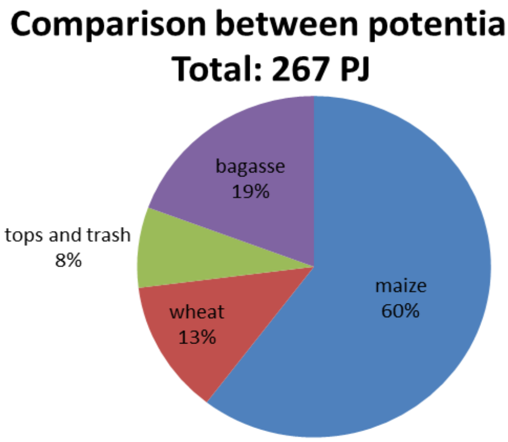

Figure 13: Comparison between the theoretical potentials of maize stover, wheat straw, sugar cane tops and trash and sugar cane bagasse.

Looking at literature, there are two (recent) studies which assess the theoretical potential for South Africa. Table 24 shows a comparison between the findings of these two studies and the results of this thesis. It is clear that there are large differences between the studies.

Type	IEA, 2010 (PJ)	Euler, 2010 (PJ)	This study (PJ)
Maize stover	147	234	161
Wheat straw	54	73	34
Sugar cane tops and trash	64	43	20
Sugar cane bagasse	114	60	52

Table 24: Comparison between the theoretical potential for South Africa as presented in the study by the IEA (2010), Euler (2010) and the results from this study. Both the IEA and Euler give the potentials in $ktonne_{dry}$, these values are converted to PJ using the HHV_{dry} shown in Table 20, Table 21, Table 22 and Table 23.

Looking at the results from the IEA, they vary quite a lot for all residue types. For maize stover to estimate by the IEA is 15PJ lower, not a huge difference but the values used to arrive at the potential are quite different. The calculations are based on data from 2007, which was a drought year, causing the crop yield to be low (2.5 tonne/ha vs 4.2 tonne/ha used in this study). Besides, the RPR differs: the IEA uses a value of 1.5, much higher than the 1.07 used here. Finally the used moisture content is 4 percent point lower than the moisture content used in this thesis.

Then, Comparing the results for wheat. The calculation by the IEA is unrepeatable. It is stated that the 2007 wheat production is 1820 ktonne, next it is said that the amount of wheat straw produced is 3027 $ktonne_{dry}$. This is strange since the stated RPR and moisture content are 1.2 and 15% respectively. Doing the calculations with the stated vales gives a potentially available amount of 1850 $tonne_{dry}$ equal to 33 PJ, almost exactly the same as the value found in this study (34 PJ).

To finalize the comparison with the IEA the Sugar cane residues results are discussed. For tops and trash as well as bagasse the IEA gives values that are much higher than the values found in this study. Again the calculation by the IEA is unrepeatable. The stated 2007 sugar cane production is 20.693 ktonne resulting in a 5985 $ktonne_{dry}$ bagasse yield. However this result does not follow from the given RPR of 0.3 and the moisture content of 75%. Doing the calculations with these given values results in a potential of 1500 $ktonne_{dry}$ or 29 PJ. Lower than the value calculated in this thesis which in turn can be explained by the low sugar cane yield in 2007. The Reasoning for the difference between the results for tops and trash are along similar lines.

Comparing the results with the results from the study by Euler, only the values on the bagasse potential are more or less the same. The difference in maize stover as well as wheat straw potential is explained by the RPR used. Euler assumes that 1.43 tonne dry stover (equal to 1.79 tonne fresh matter) is produced per tonne of grain. This seems unrealistic and is much higher than the (weighted) averages used in this study: 1.07 tonne fresh stover per tonne maize and 1.16 tonne fresh straw per tonne wheat.

Concerning sugar cane tops and trash, the difference is explained by differences in the RPR and moisture content used. Euler uses a RPR 0.28 whereas this study calculated a value of 0.2. Furthermore Euler uses a lower moisture content: 50% where this study uses a moisture content of 67%.

Despite the differences it is believed that the results of this study still hold based on the justifications provided.

9 Sustainable and technical potential

9.1 Residues required to maintain soil health

From the literature review it is concluded that a soil cover of 70%, equivalent to of 2 tonnes residue/ha is required to protect the soil against wind and water erosion. On the other hand, no guidelines for the required residue input for maintaining healthy SOC levels were found in literature. This section aims to calculate those annual required residue inputs to maintain SOC levels.

Two criteria for sustainable residue harvest can be formulated:

1. A minimum residue cover of 2 tonne residues/ha is required to provide sufficient protection from wind and rainfall-induced erosion (see section 6.1.2.1.2).
2. Sufficient residues should be left in the field to maintain at least a 2,0% SOC level (see section 9.1.1).

It may seem that this covers only the first two positive effects of residues as summarized in section 6.1.1.1 but a when soils contain a healthy amount of organic carbon this means that there are many soil organism since they feed on soil organic carbon. Besides it is also save to assume that the amount of residues required to reduce erosion below tolerable levels and to maintain soil organic carbon will be sufficient to secure a good water infiltration and drought resistance.

9.1.1 Determining healthy soil organic carbon levels

There is compelling evidence that ploughing native lands in order to convert them to agricultural lands leads to dramatic losses of SOC (du Preez, Mnkeni & van Huyssteen 2010, Ogle, Breidt & Paustian 2005b, Luo et al. 2011, du Preez, van Huyssteen & Pearson 2011). In general, agricultural soils currently have very low organic carbon levels (<0.5%). However, recent studies show that leaving residues in the field in combination with reduced or no-till practices and crop rotation has a positive impact on SOC levels and if practiced for long periods of time can restore SOC levels (Wilhelm et al. 2004, du Preez, van Huyssteen & Pearson 2011).

An important issue that must be dealt with first is determining the amount of SOC carbon required for sustainable crop production. Brady and Weil (Brady, Weil 1999) argued that a SOC content of 3% is ideal for agricultural soils. Stronkhorst and Venter (Stronkhorst, Venter 2008) stated that SOC levels between 1% and 3% are requirements for sustainable agricultural production. Accordingly, (Lal 2008) states that 1% is the critical level of SOC required for crop production. This study will use the carbon content of 2,0% for the top 20cm. In general this is considered as high, definitely for South Africa (du Preez 2012).

As an average bulk density for agricultural soils, 1,5 tonne/m^3 can be assumed (du Preez, Mnkeni & van Huyssteen 2010). Since changes in soil organic carbon due to cultivation only take place in the top 20 cm of the soil, there is about 3000 tonne soil/ha. Thus the 2,0% organic carbon content is equivalent to 60 tonne C/ha.

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9.1.2 Parameterization of input data

In order to run the model, monthly data is required on: temperature, rainfall, potential evaporation, presence of a growing crop and the clay percentage of the soil. Below, these variables are parameterized. As actual input for the model the original data is used but the parameterization below is useful when discussing the data.

	Very low	Low	High	Very high
Annual rainfall (mm/yr)	<600	600 - 800	800 - 1000	>1000
Average mean air temperature (ºC)	<5	5 - 12,5	12,5 - 20	>20
Potential annual evaporation (mm/yr)	500 - 1000	1000 - 1500	1500 - 2000	>2000
Clay content of the soil (%)	<7,5	7,5 - 15	15 - 22,5	>22,5

Table 25: Parameterization of required inputs for the Rothamsted Carbon model.

Note that amount of time the soil is covered by a growing crop is not present in the input matrix. This will vary for the three different crops accounted for: maize, wheat and sugar cane.

9.1.2.1 Inputs used for the different conditions in South Africa

As mentioned in the previous sector, one of the required inputs is the months during which a growing crop is present. For South Africa, maize is generally planted in October and harvested in June, wheat is planted in June and harvested in December. Sugar cane is replanted only after 5 to 7 years, depended on the yields (du Preez 2012). Therefore the soil will be assumed to be covered by a growing crop the entire year.

The input data used for the different South African provinces are shown in the tables below. As input for the model, the original monthly data on rainfall, temperature, potential evaporation and clay content is used from the the Schultze Atlas (Schultze, Lynch 2007, Schultze, Lynch 2007, Schultze, Maharaj 2007a, Schultze, Maharaj 2007b).

	Very low	Low	High	Very high
Annual rainfall (mm/yr)	X			
Average mean air temperature (ºC)			X	
Potential annual evaporation (mm/yr)				X
Clay content of the soil (%)	X			

Table 26: Input data representative the Northern Cape Province. To run the model, detailed data was used, this generalization is for the sake of comparison.

	Very low	Low	High	Very high
Annual rainfall (mm/yr)	X			
Average mean air temperature (ºC)			X	
Potential annual evaporation (mm/yr)				X
Clay content of the soil (%)		X		

Table 27: Input data representative for the Western Cape Province. To run the model, detailed data was used, this generalization is for the sake of comparison.

	Very low	Low	High	Very high
Annual rainfall (mm/yr)	X			
Average mean air temperature (ºC)			X	
Potential annual evaporation (mm/yr)			X	
Clay content of the soil (%)		X	X	

Table 28: Input data representative for the Eastern Cape Province. To run the model, detailed data was used, this generalization is for the sake of comparison.

	Very low	Low	High	Very high
Annual rainfall (mm/yr)			X	
Average mean air temperature (ºC)			X	
Potential annual evaporation (mm/yr)			X	
Clay content of the soil (%)				X

Table 29: Input data representative for the KwaZulu-Natal Province. To run the model, detailed data was used, this generalization is for the sake of comparison.

	Very low	Low	High	Very high
Annual rainfall (mm/yr)	X			
Average mean air temperature (ºC)			X	
Potential annual evaporation (mm/yr)				X
Clay content of the soil (%)		X	X	

Table 30: Input data representative for the Free State Province. To run the model, detailed data was used, this generalization is for the sake of comparison.

	Very low	Low	High	Very high
Annual rainfall (mm/yr)	X			
Average mean air temperature (ºC)			X	
Potential annual evaporation (mm/yr)				X
Clay content of the soil (%)	X			

Table 31: Input data representative for the North West Province. To run the model, detailed data was used, this generalization is for the sake of comparison.

	Very low	Low	High	Very high
Annual rainfall (mm/yr)		X		
Average mean air temperature (ºC)			X	
Potential annual evaporation (mm/yr)				X
Clay content of the soil (%)		X	X	

Table 32: Input data representative for the Gauteng Province. To run the model, detailed data was used, this generalization is for the sake of comparison.

	Very low	Low	High	Very high
Annual rainfall (mm/yr)		X		
Average mean air temperature (ºC)			X	
Potential annual evaporation (mm/yr)			X	
Clay content of the soil (%)				X

Table 33: Input data representative Mpumalanga Province. To run the model, detailed data was used, this generalization is for the sake of comparison.

	Very low	Low	High	Very high
Annual rainfall (mm/yr)	X			
Average mean air temperature (ºC)				X
Potential annual evaporation (mm/yr)				X
Clay content of the soil (%)			X	

Table 34: Input data representative for the Limpopo Province. To run the model, detailed data was used, this generalization is for the sake of comparison.

9.1.2.2 Results from the Rothamsted Carbon Model

Table 35, Table 36 and Table 37 shows the required carbon and residue inputs for maize, wheat and sugar cane respectively. These annual inputs are required to maintain an equilibrium 2,0% (60 tonne C/ha) and 2.5% (75 tonne C/ha) SOC. The required residue inputs are calculated using a factor of 0.45 tonne C/tonne residues (on a dry basis) ((Hamelin et al. 2012).

Table 38 shows the model outputs when simulating double cropping, meaning that maize is cultivated during the summer and wheat during the winter period. The advantage of this scenario is that the soil is permanently vegetated.

Province	**2,0% SOC**		**2,5% SOC**	
	($tonne_C$/ha)	**($tonne_{dry}$/ha)**	**($tonne_C$/ha)**	**($tonne_{dry}$/ha)**
Northern Cape	2,6	5,8	3,2	7,2
Western Cape	2,1	4,6	2,6	5,7
Eastern Cape	1,9	4,2	2,3	5,2
KwaZulu-Natal	2,1	4,7	2,6	5,8
Free State	2,0	4,4	2,5	5,5
North West	2,6	5,8	3,3	7,3
Gauteng	2,0	4,4	2,5	5,5
Mpumalanga	1,9	4,1	2,3	5,1
Limpopo	2,4	5,3	3,0	6,6

Table 35: Annual required carbon and maize stover inputs to maintain SOC levels of 2.5% and 2.0% in each province regarding continuous maize cultivation.

Province	**2,0% SOC**		**2,5% SOC**	
	($tonne_C$/ha)	**($tonne_{dry}$/ha)**	**($tonne_C$/ha)**	**($tonne_{dry}$/ha)**
Northern Cape	3,0	6,7	3,8	8,3
Western Cape	2,4	5,4	3,0	6,7
Eastern Cape	2,2	4,8	2,7	6,0
KwaZulu-Natal	3,2	7,0	3,9	8,7
Free State	2,3	5,1	2,9	6,4
North West	3,0	6,7	3,7	8,3
Gauteng	2,3	5,0	2,8	6,3
Mpumalanga	2,1	4,6	2,6	5,8
Limpopo	2,7	6,0	3,4	7,4

Table 36: Annual required carbon and wheat straw inputs to maintain SOC levels of 2.5% and 2.0% in each province regarding continuous wheat cultivation.

Province	**2,0% SOC**		**2,5% SOC**	
	($tonne_C$/ha)	**($tonne_{dry}$/ha)**	**($tonne_C$/ha)**	**($tonne_{dry}$/ha)**
KwaZulu-Natal	1,9	3,5	2,3	5,2
Mpumalanga	1,6	3,0	2,0	4,5

Table 37: Annual required carbon and sugar cane tops and trash inputs to maintain SOC levels of 2.5% and 2.0% in each province regarding continuous sugar cane cultivation.

Province	2,0% SOC		2,5% SOC	
	(tonne$_C$/ha)	(tonne$_{dry}$/ha)	(tonne$_C$/ha)	(tonne$_{dry}$/ha)
Northern Cape	2,3	5,2	2,9	6,4
Western Cape	1,8	4,1	2,3	5,1
Eastern Cape	1,7	3,7	2,1	4,6
KwaZulu-Natal	1,9	4,1	2,3	5,1
Free State	1,8	4,0	2,2	4,9
North West	2,3	5,2	2,9	6,5
Gauteng	1,8	3,9	2,2	4,9
Mpumalanga	1,6	3,6	2,0	4,5
Limpopo	2,1	4,6	2,6	5,8

Table 38: Annual required carbon and residue inputs to maintain SOC levels of 2.5% and 2.0% in each province regarding double cropping, growing maize during the summer and wheat during the winter.

9.1.2.3 Above ground residues, below ground residues and rhizodeposition

The calculated required organic carbon inputs can stem from three sources: above ground residues, below ground residues and rhizodeposition. The latter consists of root exudates and other root borne organic substances released during root growth, including root hairs and fine roots sloughed off by root elongation (Kuzyakov, Schneckenberger 2004).

The below ground residues and rhizodeposition are an important contributor to soil organic carbon(Wilhelm et al. 2004, Molina et al. 2001). Several articles state that the relative contribution of below ground residues to SOC is greater than that of above ground residues since the carbon is more efficiently converted into SOC (Wilhelm et al. 2004). The fraction of C that is incorporated into SOC is ranges from 37% to 50% for below ground biomass versus 11% to 13% for above ground residues. The difference is attributed to the slower decomposition of roots due to the high lignin content and lesser soluble carbon.

The production of the above ground harvest residues was discussed in section 8.1, below the production of below ground residues and rhizodeposition is discussed.

To start with the below ground residues, from Hamelin et al. (Hamelin et al. 2012), the ratio between the below ground residues and the primary yield is calculated as 0.42 for maize and 0.74 for winter wheat. Clapp (Clapp et al. 2000) reports a similar value for maize, 0.44. With regard to sugar cane Smith et al. (Smith, 2005) state a root shoot ratio of 0.2

There is only little data on the amount of carbon plants loose in the form of rhizodeposition and differences between different studies are big. Kuzyakov (Kuzyakov, Schneckenberger 2004) provides a comprehensive review of the studies on rhizodepostion and concluded that due to these differences only rough estimates could be provided. He describes the following partitioning of the total below ground translocated carbon:

- 50% is incorporated into root tissue
- 33% is respired by roots and microorganisms in the rhisosphere.
- 25% remains below ground in the soil and microorganisms.

Using this relation and the just described data on the production of root tissue, the amount of rhizodeposition produced can be calculated by dividing the production of root tissue by two. The results are shown in Table 39.

Sugar cane is an exception since after harvest only 17% of the roots die instead of all the roots as is the case with annual crops like maize and wheat (Ball-Coelho et al. 1992).

Crop	Ratio Root : crop yield	Ratio Rhizodep. : crop yield	Ratio (Root+Rhizodep.) : crop yield
Maize	0,43	0,22	0,65
Wheat	0,74	0,37	1,11
Sugar cane	0,20	0,10	0,30

Table 39: Production of roots and rhizodepostion expressed as a ratio to the crop yield for maize, wheat and sugar cane. The ratio for the combined production of roots and rhizodeposition is also given. It is important to note that since sugar cane is perennial crop, only 17% of the roots die after harvest(Ball-Coelho et al. 1992). Ratios on dry basis.

9.1.3 Conclusion and discussion SOC

Table 35, Table 36 and Table 37 provide an overview of the required amount of both carbon and residues to maintain SOC carbon at 2.0% (60 tonne C/ha) and 2.5% (75 tonne C/ha). Below the most import conclusions are discussed.

9.1.3.1 The effect of the permanent presence of a growing crop

In general it can be concluded that the inputs required are the lowest for sugar cane production, this is due to the fact the sugar cane is a perennial crop. The year round presence of a growing crop slows carbon decay. In general the presence of a crop improves soil quality, as in stimulates the biological activity of the soil and it sequesters carbon (Steinke 2012). Maize and wheat require very similar inputs although the maize inputs are a little lower under all conditions since the soil is fallow for a substantial part of the year.

Table 38 then shows the annual residues inputs required to maintain both 2.0% and 2.5% SOC. When these results are compared to the continuous maize of wheat cultivation, the residue inputs are 11% to 24% lower. Since the soil is permanently covered by a growing crop carbon decays slower, causing it to accumulate. When enough water is available to produce two crops in a year, double cropping is a very interesting option. The fact that two crops are harvested each year means that the annual crop and residues (above and below ground) production are increased while the required carbon input decreases. In South Africa, double cropping is generally only possible under irrigation due to the water shortage (du Preez 2012).

9.1.3.2 Differences between provinces: soil and climatic variation

Per crop, there are large differences between the results for the South African provinces. These differences can be explained by the clay content and the climatic conditions.

A high clay content is favourable as this results in more carbon being converted to humus instead of to CO_2, see also section 1.1.2. Besides the positive effect on SOC dynamics, clayey soil are typically more fertile and have a higher water holding capacity than sandy soils(du Preez 2012).

Next to the influence of the clay percentage, the climatic conditions also play in important role. The very warm and dry provinces where also the potential evaporation is high, such as the Northern Cape and Limpopo, require larger than average inputs to maintain SOC.

Mpumalanga scores best for all crops. The very high clay content means little C is lost as CO_2, furthermore the high temperature and potential evaporation combined with low (but not very low) rainfall cause that the decay of organic matter is relatively slow, leading to accumulation of organics and thus carbon.

It is interesting to compare the Free State and KwaZulu-Natal, conditions are very different but the required maize residues inputs are more or less the same. In the Free State there is less clay so less C is converted to humus and more to CO_2 compared to KwaZulu-Natal. On the other hand, the warm and moist conditions in KwaZulu-Natal mean a high decomposition rate, and thus slower accumulation.

It is questionable whether the results described above are in line with reality. The 'goal' is to get carbon in stable forms, i.e. humus, which is achieved by descending the chain in Figure 34. Thus, by decomposition of organic matter eventually resulting in a part of the fresh material converted into humus. If the decomposition rate is low (as in the Free State) the carbon accumulates in the form of plant matter, while in more tropical condition (as in KwaZulu-Natal) more humus is formed due to the higher decomposition rate. The latter seems to be more favourable.

Long term field data on SOC dynamics are required to be able to conclude the discussion from the previous paragraphs, unfortunately such data is not available for South Africa(Steinke 2012).

9.1.3.3 Productivity of soils depleted from SOC

As discussed SOC is an important parameter and high SOC levels have shown to increase crop yields. On the contrary, the majority of South African soils currently have SOC levels of less than 0.5% ((du Preez 2012)) but still they are able to support agricultural production. This suggests that even soils of a very poor quality have the capacity to support a basic crop production.

9.1.3.4 The effect of tillage

It is important to note that the effect of tillage is not accounted for the Rothamsted carbon model which is based on a conventional tilled agricultural production system ((Coleman 2012). In literature, evidence can be found suggesting an increase in SOC or no change in SOC as an effect of a switch from conventional till to no-till. In general, SOC storage in the top 7.5 cm layer of the soil is greater under no-till compared to conventional till whereas the opposite is true for depths below 7.5 cm (Wilhelm et al. 2004).

Figure 14 shows a that no-till plus a winter cover crop increases SOC levels a up to a depth of 8cm, switching to conventional till without a cover crop causes a decline in SOC levels in the first year and a stabilization thereafter. Figure 15 clearly indicates that a minimum tilled corn-wheat-soybean-wheat rotation has higher SOC levels after 10 year than similar system that was conventional tilled.

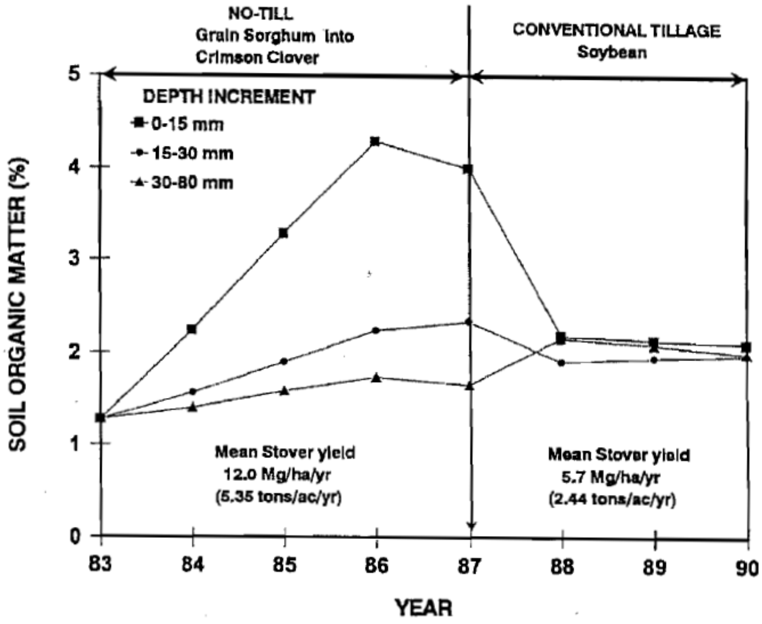

Figure 14: Effects of tillage and winter cover crop on organic matter content near the top of the soil surface (8cm)(Reicosky et al. 1995).

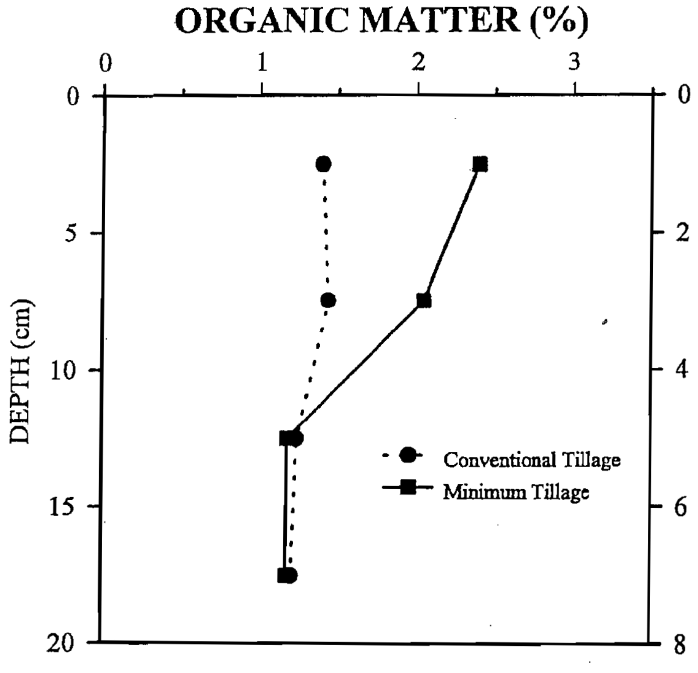

Figure 15: Soil organic matter in the soil after 10 years of corn-wheat-soybean-wheat rotation for conventional and minimum tillage (Reicosky et al. 1995).

Ogle et al. (Ogle, Breidt & Paustian 2005a) made a comprehensive review of 126 studies in order to quantify the effect of changing agricultural management on soil organic carbon. It is noticed that in more than half of the reviewed studies the response ratio (the ratio of soil organic carbon content in reduced or no-till treatment relative to conventional tillage) is positive. Although there are studies that do not observe a change in SOC storage (response ratio = 1) or even a decrease in SOC storage (resonse ratio < 1) in general it can be concluded that reduced and no-till practices most often increase SOC storage.

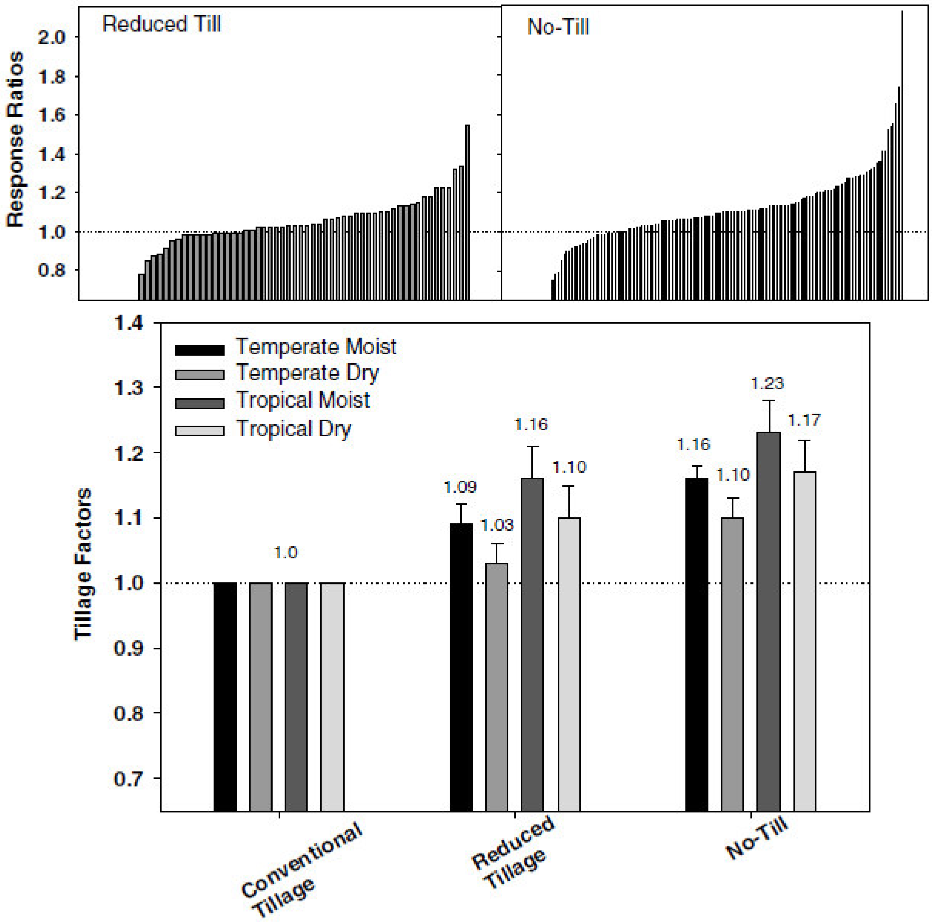

Figure 16: Response ratios (soil organic carbon content in reduced or no-till treatment relative to conventional tillage) from individual studies (top) and statistically derived factor estimates (bottom) for the change in SOC storage as an effect of a change from conventional tillage to reduced or no-till after 20 years(Ogle, Breidt & Paustian 2005a).

9.2 Residue demand by competing uses and losses from burning.

Maize straw and wheat stover
In South Africa it is common practice to feed cattle on maize residues trough the winter season in areas where these are available. It is a cheap way for winter feeding and a possibility for the farmer to generate some additional income. Because of the cost involved with baling residues, the cattle graze the maize residues in the field. The average duration of this period is about 70 days, limited by the window between harvest and field preparation for the coming season (Crichton, Gertenbach & van Henning 1998a). Wheat straw is commonly used for animal bedding during the winter period (Department of Agriculture, Forestry and Fisheries. Republic of South Africa 2010). The winter period of approximately 90 days starts in June and ends in August.

Calculation of demand
The demand for maize stover and wheat straw is calculated according to Equation 15 and Equation 16. Since cattle graze on maize stover in the field and wheat straw is traded in the informal market, no data was available on the fraction of the livestock population using residues (Crichton, Gertenbach & van Henning 1998b, Siemons et al. 2004). On the one hand it is common in South Africa to produce both crops and livestock and those farmers use the residues from crop production for livestock production. On the other hand it is unlikely that farmers use residues when they do not have mixed farms because farms are scattered over a large area. It is therefore assumed that half of the livestock population uses residues. As regards the size of the livestock population, only the commercial livestock population is accounted since this study only accounts for commercial crop production and communal livestock farmers don’t buy residues from commercial crop farmers. The calculated demand is shown in Table 40 and Table 41.

Loss of tops and trash trough burning
As mentioned in section 6.2.2, despite a visible trend away from burnt sugar cane harvesting approximately 85% of the sugar cane produced in South Africa is still burnt prior to harvest (Muir, Eggleston & Barker 2009). Obviously this crushes the amount of sugar cane trash potentially available and it is particularly regrettable as burning negatively effects water, soil organic carbon and nitrogen conservation (van Antwerpen et al. 2002). The technical potential after correcting for burning losses is shown in Table 46 Table 47.

Province	Livestock population[1] ('000 heads)		Maize stover demand (ktonne/yr)		
	Cattle		Cattle		
	Dairy	Beef	Dairy	Beef	Total
Northern Cape	25	466	2	51	53
Western Cape	280	203	28	22	50
Eastern Cape	315	612	31	67	98
KwaZulu-Natal	318	955	32	104	136
Free State	293	1962	29	215	244
North West	114	1154	11	126	138
Gauteng	75	201	7	22	29
Mpumalanga	154	701	15	77	92
Limpopo	18	420	2	108	110
Total	1.592	6.674	159	1.721	1.879

Table 40: Size of the commercial livestock population and the required maize stover demand for feed, calculated according to Equation 15, assuming 50% of the cattle feeds on residues (see section 9.2). Livestock population based on (National Department of Agriculture 2012).
[1] Only the commercial livestock population is taken into account as only these animals are fed from the commercial farming residues.

Province	Livestock population[1] ('000 heads)				Wheat straw demand (ktonne/yr)				
	Cattle				Cattle				
	Dairy	Beef	Sheep[2]	Pigs[2]	Dairy	Beef	Sheep	Pigs	Total
Northern Cape	25	466	740	48	2	31	33	1	68
Western Cape	280	203	728	48	19	14	33	1	66
Eastern Cape	315	612	1.398	91	21	41	63	2	128
KwaZulu-Natal	318	955	1.920	125	21	64	86	3	175
Free State	293	1.962	3.400	222	20	132	153	5	310
North West	114	1.154	1.912	125	8	78	86	3	174
Gauteng	75	201	416	27	5	14	19	1	38
Mpumalanga	154	701	1.289	84	10	47	58	2	118
Limpopo	18	420	660	43	1	28	30	1	60
Total	1.592	6.674	12.465	814	107	450	561	18	1.137

Table 41: Size of the commercial livestock population and the wheat straw demand for bedding, calculated according to Equation 16**,** assuming 50% of the livestock population uses straw for bedding (see section 9.2). Livestock population based on (National Department of Agriculture 2012).
[1] Only the commercial livestock population is taken into account as only these animals are fed from the commercial farming residues.
[2] The allocation of sheep and pig production to different provinces is unknown and was done based on the known allocation of cattle production.

9.3 Sustainable and technical potential

Now both the amount of residues required to maintain soil health and the demand for residues by competing uses are known, the sustainable and technical potential can be calculated.

9.3.1 Results

Now the minimum residue cover required to control soil erosion, the residue inputs to maintain SOC levels at either 2,0% or 2,5% and the demand for residues by competing uses are known, the actual technical potential for South Africa is calculated. Table 42 and Table 43 show the technical potential for maize stover, maintaining 2.0% SOC and 2.5% SOC respectively. Table 44 and Table 45 show the same for wheat straw and Table 46 and Table 47 for sugar cane tops and trash

The results for sugar cane bagasse, shown in Table 48 are different. Since it is a process residue, the SOC level is not relevant as bagasse cannot be left in the field. Therefore, no sustainable potential is calculated. Since the majority of the produced bagasse is used by the mills for internal power production (Euler 2010), which is obviously an energy use, the demand by competing uses is estimated to be zero.

Figure 17 shows a comparison between the three different potentials (in PJ) and the contribution of each residue type to the total potential.

Province	Theo. potential[1] (tonne$_{dry/ha}$)	Below ground[2] (tonne$_{dry/ha}$)	Maintain SOC[3] (tonne$_{dry}$/ha)	Sus. potential (tonne$_{dry}$/ha)	Sus. potential (ktonne$_{dry}$)	Comp. uses[4] (ktonne$_{dry}$)	Tech potential (ktonne$_{dry}$)	Sus. Potential (PJ)	Tech. potential (PJ)
Northern Cape	8,43	6,09	5,78	6,43	318	53	265	**5,8**	**4,8**
Western Cape	7,10	4,91	4,58	5,10	17	50	0	**0,3**	**0,0**
Eastern Cape	4,46	2,78	4,16	2,46	38	98	0	**0,7**	**0,0**
KwaZulu-Natal	4,69	2,96	4,67	2,69	208	136	0	**3,8**	**0,0**
Free State	3,53	2,09	4,42	1,20	1.157	244	913	**21,1**	**16,6**
North West	2,93	1,68	5,84	0,00	0	138	0	**0,0**	**0,0**
Gauteng	3,97	2,41	4,40	1,97	199	29	169	**3,6**	**3,1**
Mpumalanga	4,27	2,64	4,11	2,27	1.038	92	946	**18,9**	**17,2**
Limpopo	3,44	2,03	5,29	0,18	8	110	0	**0,1**	**0,0**
Total					**2.982**	**1.879**	**2.293**	**54,3**	**41,7**

Table 42: Technical Sustainable and technical potential for bioenergy generation from **maize stover** while maintaining **2.0% SOC.**
[1] Theoretical potential taken from Table 20.
[2] Below ground residues calculated with the ratios from Table 39.
[3] Maintaining SOC, the amount of residues (above and below ground) required to maintain 2,0% SOC see Table 35.
[4] Demand for residues by competing uses taken from Table 40.

Province	Theo. potential[1] (tonne$_{dry/ha}$)	Below ground[2] (tonne$_{dry/ha}$)	Maintain SOC[3] (tonne$_{dry}$/ha)	Sus. potential (tonne$_{dry}$/ha)	Sus. potential (tonne$_{dry}$)	Comp. uses[4] (ktonne$_{dry}$)	Tech potential (ktonne$_{dry}$)	Sus. Potential (PJ)	Tech. potential (PJ)
Northern Cape	8,43	6,09	7,18	6,43	318	53	265	**5,8**	**4,8**
Western Cape	7,10	4,91	5,71	5,10	17	50	0	**0,3**	**0,0**
Eastern Cape	4,46	2,78	5,18	2,06	32	98	0	**0,6**	**0,0**
KwaZulu-Natal	4,69	2,96	5,80	1,85	143	136	0	**2,6**	**0,0**
Free State	3,53	2,09	5,51	0,11	104	244	0	**1,9**	**0,0**
North West	2,93	1,68	7,27	0,00	0	138	0	**0,0**	**0,0**
Gauteng	3,97	2,41	5,47	0,91	92	29	63	**1,7**	**1,1**
Mpumalanga	4,27	2,64	5,11	1,80	822	92	730	**15,0**	**13,3**
Limpopo	3,44	2,03	6,60	0,00	0	110	0	**0,0**	**0,0**
Total					**1.528**	**1.879**	**1.058**	**27,8**	**19,2**

Table 43: Sustainable and technical potential for bioenergy generation from **maize stover** while maintaining **2.5%**.
[1] Theoretical potential taken from Table 20.
[2] Below ground residues calculated with the ratios from Table 39.
[3] Maintaining SOC, the amount of residues (above and below ground) required to maintain 2,5% SOC see Table 35.
[4] Demand for residues by competing uses taken from Table 40.

Province	Theo. potential[1] ($tonne_{dry/ha}$)	Below ground[2] ($tonne_{dry/ha}$)	Maintain SOC[3] ($tonne_{dry}$/ha)	Sus. potential ($tonne_{dry}$/ha)	Sus. potential ($ktonne_{dry}$)	Comp. uses[4] ($ktonne_{dry}$)	Tech. potential ($ktonne_{dry}$)	Sus. potential (PJ)	Tech. potential (PJ)
Northern Cape	5,1	6,2	6,7	3,1	132	68	65	**2,35**	**1,15**
Western Cape	2,5	2,3	5,4	0,0	0	66	0	**0,00**	**0,00**
Eastern Cape	3,5	3,6	4,8	1,5	7	128	0	**0,12**	**0,00**
KwaZulu-Natal	4,2	4,7	7,0	1,9	13	175	0	**0,23**	**0,00**
Free State	2,4	2,2	5,1	0,0	0	310	0	**0,00**	**0,00**
North West	4,6	5,3	6,7	2,6	63	174	0	**1,12**	**0,00**
Gauteng	4,9	5,9	5,0	2,9	5	38	0	**0,10**	**0,00**
Mpumalanga	4,5	5,1	4,6	2,5	20	118	0	**0,35**	**0,00**
Limpopo	4,4	5,1	6,0	2,4	39	60	0	**0,69**	**0,00**
					279	**1.137**	**65**	**4,96**	**1,15**

Table 44: Sustainable and technical potential for bioenergy generation from **wheat straw** while maintaining **2.0% SOC**.
[1] Theoretical potential taken from Table 21.
[2] Below ground residues calculated with the ratios from Table 39.
[3] Maintaining SOC, the amount of residues (above and below ground) required to maintain 2,0% SOC see Table 36.
[4] Demand for residues by competing uses taken from Table 41.

Province	Theo. potential[1] ($tonne_{dry/ha}$)	Below ground[2] ($tonne_{dry/ha}$)	Maintain SOC[3] ($tonne_{dry}$/ha)	Sus. potential ($tonne_{dry}$/ha)	Sus. potential ($ktonne_{dry}$)	Comp. uses[4] ($ktonne_{dry}$)	Tech. potential ($ktonne_{dry}$)	Sus. potential (PJ)	Tech. potential (PJ)
Northern Cape	5,1	6,2	8,3	3,0	127	68	59,20	**2,26**	**1,05**
Western Cape	2,5	2,3	6,7	0,0	0	66	0,00	**0,00**	**0,00**
Eastern Cape	3,5	3,6	6,0	1,2	5	128	0,00	**0,09**	**0,00**
KwaZulu-Natal	4,2	4,7	8,7	0,2	1	175	0,00	**0,02**	**0,00**
Free State	2,4	2,2	6,4	0,0	0	310	0,00	**0,00**	**0,00**
North West	4,6	5,3	8,3	1,6	39	174	0,00	**0,69**	**0,00**
Gauteng	4,9	5,9	6,3	2,9	5	38	0,00	**0,10**	**0,00**
Mpumalanga	4,5	5,1	5,8	2,5	20	118	0,00	**0,35**	**0,00**
Limpopo	4,4	5,1	7,4	2,1	33	60	0,00	**0,59**	**0,00**
					230	**1.137**	**59**	**4,09**	**1,05**

Table 45: Sustainable and technical potential for bioenergy generation from **wheat straw** while maintaining **2.5% SOC**.
[1] Theoretical potential taken from Table 21.
[2] Below ground residues calculated with the ratios from Table 39.
[3] Maintaining SOC, the amount of residues (above and below ground) required to maintain 2,5% SOC see Table 36.

[4] Demand for residues by competing uses taken from Table 41.

Province	Theo. potential[1] (tonne$_{dry/ha}$)	Below ground[2] (tonne$_{dry/ha}$)	Maintain SOC[3] (tonne$_{dry}$/ha)	Sus. potential (tonne$_{dry}$/ha)	Sus. potential (ktonne$_{dry}$)	Burning losses[4] (%)	Tech. potential (ktonne$_{dry}$)	Sus. potential (PJ)	Tech. potential (PJ)
Northern Cape	-	-	-	-	-	-	-	-	-
Western Cape	-	-	-	-	-	-	-	-	-
Eastern Cape	-	-	-	-	-	-	-	-	-
KwaZulu-Natal	4,0	2,7	3,5	2,0	481	85%	72	**8,04**	**1,21**
Free State	-	-	-	-	-	-	-	-	-
North West	-	-	-	-	-	-	-	-	-
Gauteng	-	-	-	-	-	-	-	-	-
Mpumalanga	4,0	2,7	3,0	2,0	120	85%	18	**2,01**	**0,30**
Limpopo	-	-	-	-	-	-	-	-	-
Total					**602**		**90**	**10,0**	**1,51**

Table 46: Sustainable and technical potential for bioenergy generation from **sugar cane tops and trash** while maintaining **2.0% SOC**.
[1] Theoretical potential taken from Table 22.
[2] Below ground residues calculated with the ratios from Table 39. Note that only 17% of the sugar cane roots die after harvest (Ball-Coelho et al. 1992).
[3] Maintaining SOC, the amount of residues (above and below ground) required to maintain 2,0% SOC see Table 37.
[4] 85% of the sugar cane fields are burnt before harvest.

Province	Theo. potential[1] (tonne$_{dry/ha}$)	Below ground[2] (tonne$_{dry/ha}$)	Maintain SOC[3] (tonne$_{dry}$/ha)	Sus. potential (tonne$_{dry}$/ha)	Sus. potential (ktonne$_{dry}$)	Burning losses[4] (%)	Tech. potential (ktonne$_{dry}$)	Sus. potential (PJ)	Tech. potential (PJ)
Northern Cape	-	-	-	-	-	-	-	-	-
Western Cape	-	-	-	-	-	-	-	-	-
Eastern Cape	-	-	-	-	-	-	-	-	-
KwaZulu-Natal	4,0	2,7	5,2	1,5	368	85%	55	**6,14**	**0,92**
Free State	-	-	-	-	-	-	-	-	-
North West	-	-	-	-	-	-	-	-	-
Gauteng	-	-	-	-	-	-	-	-	-
Mpumalanga	4,0	2,7	4,5	2,0	120	85%	18	**2,01**	**0,30**
Limpopo	-	-	-	-	-	-	-	-	-
Total					**488**		**73**	**8,15**	**1,22**

Table 47: Sustainable and technical potential for bioenergy generation **from sugar cane tops and trash** while maintaining **2.5% SOC**.
[1] Theoretical potential taken from Table 22.
[2] Below ground residues calculated with the ratios from Table 39. Note that only 17% of the sugar cane roots die after harvest (Ball-Coelho et al. 1992).
[3] Maintaining SOC, the amount of residues (above and below ground) required to maintain 2,5% SOC see Table 37.

[4] 85% of the sugar cane fields are burnt before harvest.

Province	Theo. potential[1] (tonne$_{dry/ha}$)	Area (kha)	Comp. uses[2] (ktonne$_{dry}$)	Tech. potential (ktonne$_{dry}$)	Tech. potential (PJ)
Northern Cape	-	-	-	-	**-**
Western Cape	-	-	-	-	**-**
Eastern Cape	-	-	-	-	**-**
KwaZulu-Natal	8,8	247	0	2179	**41,4**
Free State	-	-	-	-	**-**
North West	-	-	-	-	**-**
Gauteng	-	-	-	-	**-**
Mpumalanga[2]	8,8	62	0	545	**10,3**
Limpopo	-	-	-	-	**-**
Average[4]/total			**0**	**2723**	**51,7**

Table 48: Technical potential for bioenergy generation **from sugar cane bagasse**. Sustainable potential is equal to the technical potential for sugar cane bagasse.
[1] Theoretical potential taken from Table 23.
[2] Virtually all bagasse for energy production (Euler 2010); the internal power demand of the sugar mills.

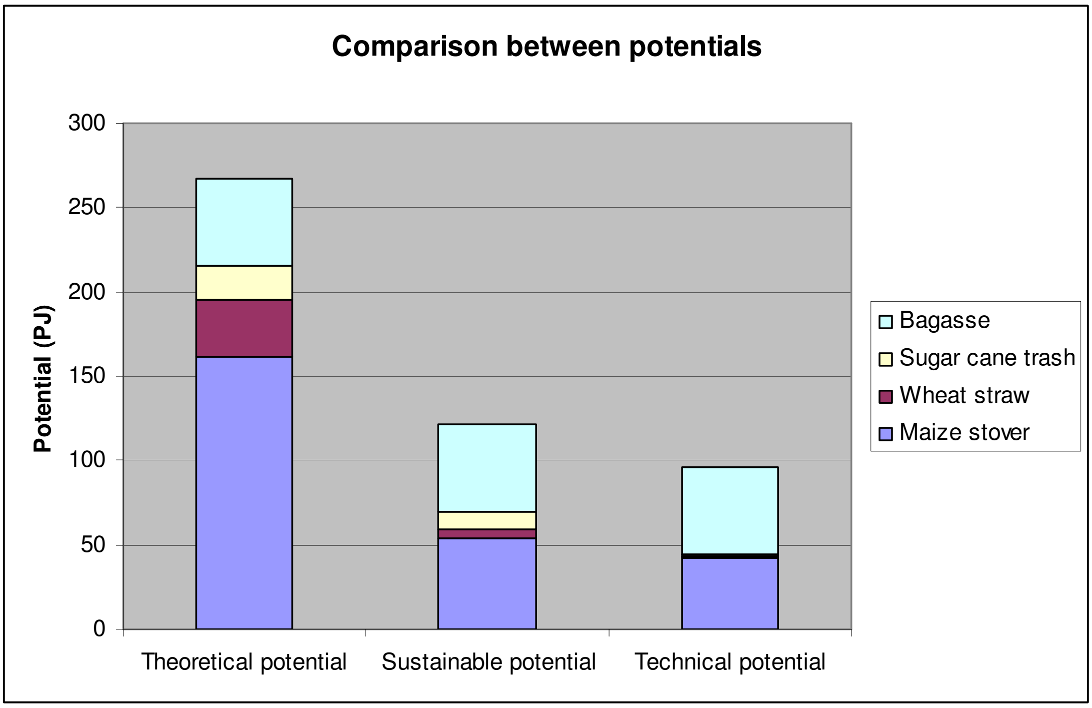

Figure 17: Comparison between the theoretical potential (267 PJ), sustainable potential (121 PJ) and technical (96 PJ) potential, showing the contribution of the residue types to the totals.

9.4 Conclusion and discussion

9.4.1 Sustainable potential

High yields required
It is concluded that with increasing yields, an increasing amount of residues can be removed since the amount of residues required to maintain soil productivity is not dependent on crop yield. The moderate yields in South Africa make that the sustainable potential (121 PJ) is less than half of the theoretical potential (267 PJ). However, looking at the average yields in the U.S.A. (maize: ~10 tonne/ha and wheat: ~3 tonne/ha), Europe (maize: ~7 tonne/ha and wheat: ~5 tonne/ha) and Brazil (sugar cane: ~75 tonne/ha) the sustainable potential in these countries will be higher and the gap with the theoretical potential smaller (yields based on FAOSTAT).

Limiting factor: erosion and SOC
For the conditions in South Africa, the 2 tonne/ha residue cover to control erosion becomes the limiting factor when crop yields exceed ~4 tonne/ha for maize and wheat and ~60tonne/ha for sugar cane. For these yields the amount of below ground residues is almost sufficient to maintain a 2,0% SOC level. For yields lower than the above stated values, the not enough below ground residues are produced and thus more than 2 tonne/ha of the above ground residues must remain in the field to maintain a 2,0% SOC level. Since the semi arid climate in South Africa is not favourable for SOC accumulation these thresholds may be lower in countries with a more favourable climate such as Brazil (du Preez 2012).

These expected lower thresholds together with the above stated average yields imply that in the U.S.A., Europe and Brazil the 2 tonne/ha cover required for erosion control is the limiting factor and it is not required to take SOC levels into account (exept for wheat in the U.S.A.). However long term (>20 years) field trials are required to determine whether this indeed the case because the Rothamsted Organic Carbon Model used to predict the required residues inputs in this study is a relatively simple model while the SOC dynamics are quite complex. Although it has shown to successfully predict SOC changes in varying conditions (see 1.1.3 in Appendix 1).

Double cropping
Comparing the required residue inputs to maintain 2.0% SOC when producing maize during the summer and wheat during the winter (double cropping) to continuous maize or wheat production, it is calculated that that the required annual residue inputs are decreased between 11% and 24%. Since double cropping implies larger residue (above ground as well as below ground) yields and it is generally considered to be better if a soil is cultivated instead of bare, it is an attractive option in areas where production is not limited by water availability. Unfortunately such areas are sparse in South Africa (Steinke 2012).

9.4.2 Technical potential

Potential in South Africa
From Figure 17 it can be seen that although the theoretical potential (267 PJ) is about ~5% of South Africa's primary energy demand[7], the technical potential (96 PJ) is limited. The sustainable available amount of wheat straw is fully demanded as animal bedding and 85% of the sugar cane trash potential is lost by open field burning prior to cane harvest.

The remaining 96 PJ consist for 52PJ of bagasse which is used to generate the sugar mills internal power demand. However this is done in an inefficient way as there is no incentive for the mills to install efficient boilers; there is no buyback rate for electricity and no market for bagasse. Euler (Euler 2010) calculates that only 20% - 30% of the produced bagasse is required to power the sugar mills if state-of-the-art boilers would be installed. The other half (42 PJ) of technical potential results from maize stover. 17 PJ is located favourably in Mpumalanga as most coal fired power plants as well as SASOL's coal to liquids facility is located here. Another 17 PJ is located in the Free State and can potentially be co-fired in one of the coal fired power plants in the province.

Banning open field burning
An interesting point is that banning open field burning prior to sugar cane harvest would not only result in ~8.5 PJ additional potential but also prevent the CO_2 emissions resulting from burning and is beneficial to soil quality (Nel 2011). The sugar cane trash can then be harvested with the cane stalks and converted into energy by the sugar mills.

Animal uses
South Africa has an extensive livestock sector and its demand for residues reduces the sustainable potential by ~14%. However the calculations are based on rough estimates regarding the percentage of the livestock using residues and the duration of the grazing season and therefore require a more detailed assessment. If these factors are known the demand can be calculated according to Equation 15 and Equation 16. Comparing the technical potential to other countries, again the picture looks brighter. In the U.S. the demand for residues by competing uses is only 5% (Euler 2010).
Comparison to other studies

[7] The total primary energy supply of South Africa is 5.63 EJ (IEA 2008).

Similar to section 8.2 where the calculated theoretical potential is compared to other studies on South Africa, this section compares the calculated technical potential with potentials presented by Euler (Euler 2010). and the IEA (IEA 2010).

To start with **maize stover**, the IEA estimates that 90% of the produced stover is used as fodder or for nutrient cycling but does not provide an actual number. Euler's estimate is more than three times the potential resulting from this study. However, first of all it is based on the seemingly unrealistic assumption that 1 $tonne_{dry}$ stover can be removed per tonne of maize produced while leaving 30% of the residues in the field (generally literature uses a residue production of 1 tonne fresh matter per tonne of maize) and second, assuming that 5% of the residues is used for competing uses based on U.S. figures.

For **wheat straw** the differences are explained in a similar fashion. The IEA again assumes 90% of the produced straw is used as fodder, fuel or for competing uses but doesn't provide an actual potential. The potential calculated by Euler is based on the same seemingly unrealistic assumptions used for maize stover calculations.

Regarding **sugar cane tops and trash** the number by the IEA is based on a 10% availability, similar to the 15% availability assumed in this study but the higher theoretical potential (see discussion section 8.2) explains the difference. The figure stated by Euler is much higher as he calculates the amount of trash that could be available if cane was harvested without burning (while this study deducts the amount lost as by burning).

Finally looking into **sugar cane bagasse**, the IEA again estimates a 10% availability. Because they assess the availability for biofuel production they account the energy production by the sugar mills as a competing use. Euler states a value similar to this study however the calculation method is quite different. Euler calculates a much higher theoretical potential (see discussion section 8.2) and then deducts the bagasse used to power the sugar mill as he also energy production by the sugar mill as a competing use since he assess biomass availability.

Despite the differences it is believed that the results of this study still hold based on the justifications provided.

Type	IEA (2010) (PJ)	Euler (2010) (PJ)	This study (PJ)
Maize stover	n.a.	135	41,7
Wheat straw	n.a.	43	1,15
Sugar cane trash	6,41	42,8	1,51
Sugar cane bagasse	11,4	54,2	51,7

Table 49: Comparison between the technical (PJ) potential presented by Euler (Euler, 2010), the IEA (REF IEA) and the potential calculated in this study.

10 Residue supply cost

The aim of this chapter is to gain insight into the optimal collection method for each crop, therefore the conventional residue collection methods are compared with innovative new methods which aim to harvest both crop and residue in a single pass. It is important to note that residues are considered to be a by-product and thus no cost for crop growth (e.g. seed or fertilizer cost) will be allocated to the residue supply cost.

There are multiple possibilities for harvesting the crop residues, these different possibilities range from conventional harvest methods to state-of-the-art harvest methods that aim to harvest both the crop and the residues in a cost-efficient manner. Each method has a specific harvest efficiency but, some methods deliberately aim to only harvest a fraction of the available residues due to sustainability considerations. The costs of the different harvest methods for each crop are shown in the sections below.

10.1 Assumptions

In order to make all the required calculations a large number of assumption had to made, these assumptions are listed below.

Fuel Price	8,4	R/l	Euler, 2010
Fuel consumption	0,22	l/kWh	Turhollow, 2009
Lubrication oil cost	15	% of fuel cost	Turhollow, 2009
Price of skilled labor	3,4	$/hr	Euler 2010
Labor/machine	1,2	hr/hr	Sokhansj, Turhallow 2002
Exchange rate SA Rand to U.S.$ (avg 2011)	7,56	R/$	IRS 2012
Conversion rate SA Rand to Euro	10,13	R/€	IRS 2012
Real interest rate	7,5%		World Bank
Farmer profit margin	10%		Perlack, Turhallow 2003
Square bale density	163	kg/m^3	Grigson 2012
Round bale density	267	kg/m^3	Vermeer, 2012
Square bale volume (1,2mx1,28mx2,4m)	3,7	m^3	Massey Ferguson, 2012
Square bale volume (1,2m*0,88m*2,4m)	2,5	m^3	Massey Ferguson, 2012
Round bale volume (1,8m diameter)	4,1	m^3	Vermeer, 2012
Density maize stover (exiting forage blower)	48	kg/m^3	Birrell 2012
5 year average maize stover yield in SA[1]	4,42	tonne/ha	FAOSTAT 2011
5 year average wheat stover yield in SA[1]	3,34	tonne/ha	FAOSTAT 2012
5 year average sugar cane trash yield in SA[1]	11,97	tonne/ha	FAOSTAT 2013
Residue entering combine harvester (maize)	30	%	Hoskinson, 2007
Field efficiency machinery	0,9	usefull h/total h	
5 year average potassium fertilzier price (KCL)	6040	R/tonne	Grain SA, 2012
5 year average phosphate fertilizer (MAP)	5140	R/tonne	Grain SA, 2012
5 year average nitrogen fertilizer (Urea)	4280	R/tonne	Grain SA, 2012

Table 50: Assumptions used for the calculation of the

[1] Calculated using the relation between the yield and RPR established in section 4.1.1.
[2] Calculated by dividing the hourly processed amount of grain by the hourly processed amount of grain.

10.2 Maize

For a good understanding of residue harvest options, a basic knowledge of the maize harvest procedure is required. All commercial maize is harvested using a combine harvester, designed to separate the maize from the other plant parts while driving through the field (Cronje 2012). Basically all the material up from the ear of the plant is pulled into the combine where it is trashed; all material other than kernels is spread out from the back of the combine. After crop harvest, the stalks up to a height of roughly 40cm are left standing in the field, the rest of the residual material is spread out (Hoskinson et al. 2007).

Due to the interest to use maize stover for the production of second generation biofuels, especially in the USA, several new harvesting methods are being developed. These new developments aim to reduce residue harvest cost and improve the quality of the residues (e.g. less sand in bales). In the following sections the direct cost of six residue harvest methods are discussed.

10.2.1 Direct cost

10.2.1.1 Conventional round bale maize stover harvest

Required field operations
With this harvesting method, the harvesting of the crop and the residues is done separately. Because approximately half of the residues are still anchored to the ground after maize harvest, the residues need to be cut. This is best done using a flail chopper that leaves the material in a windrow (Sokhansanj, Turhollow 2002). This windrow can then be picked up by a baler. This study uses a round baler especially designed to bale maize residues which produces bales with a diameter of 1.8m (Ham 2012). The produced bales must be transported to the edge of the field where they await further transport. The most efficient way to do this is with a tractor pulled round bale collector with an integral bale loading arm. The last step is then to stack the bales using a tractor mounted bale handler (Sokhansanj, Turhollow 2002).

Collection efficiency
The conventional residue harvest method is the most efficient of all. The efficiency is estimated to be between 75% and 85% (Milhollin et al. 2011). In an older study Sokhansanj et al. (Sokhansanj, Turhollow 2002) estimate that the maximum residue removal does not exceed 70%. Since this is a much older study and it seems plausible that the collection has become more efficient since then, this study assumes a collection efficiency of 80%. The relatively high efficiency is explained by the fact that only in this collection method, the residues are cut before baling, thereby the stalks that are still anchored to the ground become available for baling.

The costs are shown in Table 51

10.2.1.2 Conventional square bale maize stover harvest

Required field operations
Similar to the round bale harvest, the residues are cut, windrowed and baled only this time a large square baler is used producing 1.2mx1.3mx2.4m bales. The collection of these bales is most efficient with a bale collector that automatically

stacks the bales. This collector/stacker can load the bales without stopping and creates a stack of bales on a tilted flatbed. The truck unloads the stacked bales using a hydraulic arm underneath the bed producing a vertical stack of bales, thereby eliminating the need for additional bale handling (Matlack 2012).

Collection efficiency
Since there is very little to no difference the collection efficiency is the same of the conventional round bale residue harvest.

The costs are shown in Table 52

10.2.1.3 Single pass maize stover harvest using the 'bale direct system'

Required field operations
The bale direct system is a new development for simultaneous crop and residue harvest which works for both maize and wheat residues. It aims to bring down residue harvest cost and to produce high quality bales with less contamination. The spreader on the combine harvester is switched of and the bale direct system conveys the residues leaving the back of the combine directly into the baler which is pulled by the combine itself. A square baler is used so the combine doesn't have to stop to discharge the bales, which would be the case when using a round baler. The baler used for the calculations produces 1,2mx0,9mx2.4m square bales as this provides the best match between combine residue output and baler capacity. The bales are collected and stacked using the above described bale collector/stacker.

Because switching off the spreader saves about as much power as is required to power the 'bale direct system' and the baler, the capacity if the combine is not reduced hereby (Foster 2012). However, square balers are relatively heavy and pulling them through the field will reduce combine capacity. Unfortunately the experience with these harvest methods is limited and therefore there is little data on this reduction in capacity. Estimates range between 0% and 15% (Foster 2012, Birrell 2012). This study assumes that the reduction in combine capacity is 10%.

Collection efficiency
The collection efficiency of the system can be varied somewhat, and is depend on the amount of residue processed by the combine. Under normal harvest operations, the combine processes about 30% of the residues (Hoskinson et al. 2007). Due to design of the maize header on the combine, not more than 30% of the residues can be collected (Birrell 2012).The collection efficiency of the system can be decreased to about 15% though (Foster 2012).

The costs are shown inTable 53 (collecting 15%) and Table 54 (collecting 30%).

10.2.1.4 Single pass maize stover harvest using a forage blower

Required field operations
Another new development, which is not commercially available yet, is the harvest of maize or wheat residues by attaching a forage blower to the combine harvester

which blows all the processed residues into a trailer. The very low density of the residues (48 kg/m^3) forms a major logistical problem (Birrell 2012). This study calculates the collection cost using large sugar cane trailers pulled by tractors driving next to the combine as these trailers have the highest capacity in terms of volume.

The combine must power the blower attachment. This reduces its capacity depending on the amount of residues collected. In test trials the amount of residues collected was varied from roughly 20% of the available residues 75% of the available residues. The corresponding combine capacity reduction varied from 0% to 20% (Birrell 2012).

Collection efficiency
Due to the use of a modified maize header on the combine, the anywhere between 20% and 70% of the available residues could be collected during test trials. The normal maize header, for instance used in the bale direct system, can harvest a maximum of 30% of the available residues (Birrell 2012).

The costs are shown Table 55 (collecting 20%) and Table 56 (collecting 70%).

10.2.1.5 Bale directly behind combine (ground pick-up)

Required field operations
This method is less advanced than the method using the bale direct system described under 3. The concept is simple, the spreader on the combine is turned off which causes the combine to drop the residues in a windrow. A square baler is pulled by the combine picks up the windrowed material. As discussed above, pulling the baler is assumed to reduce combine capacity by 10%. The produced bales are again collected by the previously described bale collector/stacker.

Collection efficiency
This method of collection residue is less efficient than the method using the bale direct system because the baler picks up the material from the ground where it is stuck between the anchored stalks. The collection efficiency is estimated to be 25% (Milhollin et al. 2011).

The costs are shown in Table 57.

10.2.1.6 Cob harvest only

Required field operations
This system is specifically designed to solely collect the cobs (after removal of the kernels), thereby returning the other residues to the soil (Milhollin et al. 2011). The combine attachment blows the cobs into a collection cart pulled behind the combine. This cart can unload into a wagon in 90 seconds. This method gives the best quality feedstock as the energy content of cobs is highest of the different residue parts.

Collection efficiency
Since the cobs account for about 12% of the total residue weight, the collection efficiency is assumed to be 12% (Milhollin et al. 2011).

The costs are shown in Table 58.

Machinery	kW	Capacity (tonne/h)	Life (h)	Annual usage (h)	Purchase price ($)	lifetime (yr)	Annuity factor	Investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
1,8m flail chopper[1]	30	5	2000	200	16.493	10,0	0,15	**2,3**	**3,4**	**0,0**	**0,0**	**0,6**	**6,2**	**0,34**
Tractor (35W)	35		16000	1500	29.428	10,7	0,14	**0,5**	**0,4**	**1,9**	**0,1**	**0,3**	**3,2**	**0,17**
Sub total								**2,8**	**3,8**	**1,9**	**0,1**	**0,9**	**9,4**	**0,52**
Round baler (1,8m diameter)[2]	112	39	1500	250	47.000	6,0	0,21	**1,0**	**0,8**	**0,0**	**0,0**	**0,2**	**2,0**	**0,11**
Tractor (123kW)	123		16000	1500	124.657	10,7	0,14	**0,3**	**0,2**	**0,9**	**0,0**	**0,1**	**1,6**	**0,09**
Sub total								**1,3**	**1,0**	**0,9**	**0,0**	**0,3**	**3,5**	**0,19**
Round bale mover (1,8m diameter)[3]	67	13	2500	500	16.328	5,0	0,25	**0,6**	**0,5**	**0,0**	**0,0**	**0,1**	**1,3**	**0,07**
Tractor (73kW)	73		16000	1500	59.148	10,7	0,14	**0,4**	**0,3**	**1,6**	**0,0**	**0,2**	**2,7**	**0,15**
Sub total								**1,1**	**0,9**	**1,6**	**0,0**	**0,4**	**3,9**	**0,22**
Telscopic bale handler[4]	60	18	4000	1000	107.670	4,0	0,30	**1,8**	**1,4**	**0,0**	**0,0**	**0,3**	**3,6**	**0,20**
Tractor (60 kW)	60		16000	1500	44.669	10,7	0,14	**0,2**	**0,2**	**0,9**	**0,0**	**0,1**	**1,5**	**0,08**
Sub total								**2,0**	**1,6**	**0,9**	**0,0**	**0,5**	**5,1**	**0,28**
Total								**7,2**	**7,3**	**5,3**	**0,2**	**2,0**	**22,0**	**1,21**

Table 51: Direct cost of **conventional round bale** maize stover harvest.
[1] Adapted from Department of agriculture forestry and fisheries (Department of agriculture forestry and fisheries. Republic of South Africa 2010).
Capacity in ha/h and power demand assumed to be similar to the 1,8m disc chopper; capacity in tonne/h calculated using the 10 year avg. residue yield.
[2] Based on the 'Vermeer 605 Super M cornstalk special' baler(Ham 2012); capacity based on production of 40 bales/h and a field efficiency of 90%; cost based on US prices
[3] Adapted from Sokhansanj (Sokhansanj, Turhollow 2002). Capacity in tonne/h based on the capacity of 11,7 bales/h which is calculated using a bale collection rate of 14 bales/h, a load capacity of 14 bales, a speed of 16km/h and an avg. distance form field to farm of 0,9km and a unloading time of 5min.
[4] Adapted from Sokhansj (Sokhansanj, Turhollow 2002) Capacity calculated from a capacity of 48 bales/h and the round bale volume and density.

Machinery	kW	Capacity (tonne/h)	Life (h)	Annual usage (h)	Purchase price ($)	lifetime (yr)	Annuity factor	Investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
1,8m flail chopper[1]	30	5	2000	200	16.493	10	0,15	**2,3**	**3,4**	**0,0**	**0,0**	**0,6**	**6,2**	**0,34**
Tractor (35W)	35		16000	1500	29.428	11	0,14	**0,5**	**0,4**	**1,9**	**0,1**	**0,3**	**3,2**	**0,17**
Sub total								**2,8**	**3,8**	**1,9**	**0,1**	**0,9**	**9,4**	**0,52**
Square baler (1,3x1,2x2,4m)[2]	134	32	3000	500	192.497	6	0,21	**2,5**	**1,5**	**0,0**	**0,0**	**0,4**	**4,5**	**0,24**
Tractor (136kW)	136	0	16000	1500	160.968	11	0,14	**0,5**	**0,4**	**1,2**	**0,0**	**0,2**	**2,2**	**0,12**
Subtotal								**3,0**	**1,9**	**1,2**	**0,0**	**0,6**	**6,7**	**0,37**
Square bale mover/stacker[3]	229	41	2500	500	179.100	5	0	**2,2**	**1,7**	**1,6**	**0,0**	**0,6**	**6,1**	**0,33**
Total								**8,0**	**7,5**	**4,6**	**0,1**	**2,0**	**22,2**	**1,22**

Table 52: Direct cost of **conventional square bale** maize stover harvest.
[1] Adapted from Department of agriculture forestry and fisheries (Department of agriculture forestry and fisheries. Republic of South Africa 2010).
Capacity in ha/h and power demand assumed to be similar to the 1,8m disc chopper; capacity in tonne/h calculated using the 10 year avg. residue yield.
[2] Based on the Massey Furgeson 2190 baler; Capacity based on the production of 60 bales/h and a field efficiency of 90%; investment cost calculated from European cost.
[3] Based on the Stinger 6500 square bale stacker collecting 1,2mx1,3m bales; cost based on US cost (Matlack 2012).

Machinery	kW	Capacity (tonne/h)	Life (h)	Annual usage (h)	Purchase price ($)	lifetime (yr)	Annuity factor	Investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
10% reduced combine capacity[1]								**8,6**	**3,4**	**2,2**	**0,0**	**1,4**	**15,6**	**0,86**
Bale direct system[2]		6	2000	300	72.500	7	0,20	**8,2**	**3,3**	**0,0**	**0,0**	**1,1**	**12,6**	**0,69**
Square baler (1,2,mx0,88mx2,4m)[3]	124	6	3.000	500	120.053	6	0,21	**8,8**	**5,3**	**0,0**	**0,0**	**1,4**	**15,5**	**0,85**
Square bale mover/stacker[4]	229	28	2.500	500	179.100	5	0,25	**3,2**	**2,5**	**2,3**	**0,0**	**0,8**	**8,9**	**0,49**
Total								**28,7**	**14,5**	**4,5**	**0,0**	**4,8**	**52,5**	**2,88**

Table 53: Direct cost of single pass maize stover harvest using the '**bale direct**' system collecting ***15%* of the available residues**.

[1] The extra cost for maize (grain) harvest due to the reduced harvest capacity are allocated to the residue harvest cost, see 4.5.3.3 for the methodology. [2] Only available in the US and Australia, cost based on US cost (Foster 2012); Capacity limited by the residue output of the combine harvester.

[3] Based on the Massey Ferguson 2170 large square baler; Capacity imited by the output of the combine harvester.

[4] Based on the Stinger 6500 square bale stacker collecting 1,2mx0,88m bales with a field efficiency of 90%(Matlack 2012)(Matlack 2012); cost based on US cost (Matlack 2012).

Machinery	kW	Capacity (tonne/h)	Life (h)	Annual usage (h)	Purchase price ($)	lifetime (yr)	Annuity factor	Investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
10% reduced combine capacity[1]								**4,3**	**1,7**	**1,1**	**0,0**	**0,7**	**7,8**	**0,43**
Bale direct system[2]		12	2.000	300	72.500	7	0,20	**4,1**	**1,6**	**0,0**	**0,0**	**0,6**	**6,3**	**0,35**
Square baler (1,2,mx0,88mx2,4m)[3]	124	12	3.000	500	120.053	6	0,21	**4,4**	**2,6**	**0,0**	**0,0**	**0,7**	**7,8**	**0,43**
Square bale mover/stacker[4]	229	28	2500	500	179.100	5	0,25	**3,2**	**2,5**	**2,3**	**0,0**	**0,8**	**8,9**	**0,49**
Total								**15,9**	**8,5**	**3,4**	**0,0**	**2,8**	**30,7**	**1,68**

Table 54: Direct cost of single pass maize stover harvest using the '**bale direct**' system collecting ***30%* of the available residues**.

[1] The extra cost for maize (grain) harvest due to the reduced harvest capacity are allocated to the residue harvest cost, see 4.5.3.3 for the methodology. [2] Only available in the US and Australia, cost based on US cost (Foster 2012); Capacity limited by the residue output of the combine harvester.

[3] Based on the Massey Ferguson 2170 large square baler; Capacity limited by the output of the combine harvester.

[4] Based on the Stinger 6500 square bale stacker collecting 1,2mx0,88m bales with a field efficiency of 90%(Matlack 2012)(Matlack 2012); cost based on US cost (Matlack 2012).

Machinery	kW	Capacity (tonne/h)	Life (h)	Annual usage (h)	Purchase price ($)	lifetime (yr)	Annuity factor	Investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
forage blower attachment[1]		8	2.000	300	415.800	7	0,20	**4,6**	**1,9**	**0,0**	**0,0**	**0,6**	**7,1**	**0,39**
Sugar cane trailer (38 tonne interlink)[2]	80	7	8.000	1.000	425.000	8	0,17	**1,5**	**0,7**	**0,0**	**0,0**	**0,2**	**2,4**	**0,13**
Tractor (83kW)	83,0	0,0	16000,0	1500,0	621043,0	10,7	0,1	**1,2**	**0,9**	**3,6**	**0,1**	**0,6**	**6,3**	**0,35**
Subtotal								**2,6**	**1,7**	**3,6**	**0,1**	**0,8**	**8,7**	**0,48**
Total								**7,3**	**3,5**	**3,6**	**0,1**	**1,4**	**15,9**	**0,87**

Table 55: Direct cost of single pass maize stover harvest using a **forage blower** attachment collecting ***20%* of the available residues**.

[1] Not commercially available; cost estimates from US cost(Birrell 2012); capacity is limited by the residue output of the combine harvester.

[2] Adapted from (Department of agriculture forestry and fisheries. Republic of South Africa 2010). Capacity calculated from a loading capacity of 114m3 equal to 5,47 tonne stover (density: 48kg/m^3), a combine output of 8 tonne stover/h, an avaerge one way distance from farm to field of 0,9km at a speed of 20km/h and allowing for 5min to couple/uncouple the trailers.

Machinery	kW	Capacity (tonne/h)	Life (h)	Annual usage (h)	Purchase price ($)	lifetime (yr)	Annuity factor	Investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
forage blower attachment[1]		27	2.000	300	415.800	7	0,20	**1,3**	**0,5**	**0,0**	**0,0**	**0,2**	**2,0**	**0,11**
20% reduced combine capacity[2]								**3,6**	**1,4**	**1,0**	**0,0**	**0,6**	**6,6**	**0,36**
Subtotal								**4,9**	**2,0**	**1,0**	**0,0**	**0,8**	**8,7**	**0,48**
Sugar cane trailer (38 tonne interlink)[3]	80	17	8.000	1.000	425.000	8	0,17	**0,6**	**0,3**	**0,0**	**0,0**	**0,1**	**1,0**	**0,05**
Tractor (83kW)	83	0	16.000	1.500	621.043	11	0,14	**0,5**	**0,4**	**1,4**	**0,0**	**0,2**	**2,5**	**0,14**
Subtotal								**1,0**	**0,7**	**1,4**	**0,0**	**0,3**	**3,5**	**0,19**
Total								**5,9**	**2,6**	**2,5**	**0,0**	**1,1**	**12,1**	**0,67**

Table 56: Direct cost of single pass maize stover harvest using a **forage blower** attachment collecting ***70%* of the available residues**.

[1] Not commercially available; cost estimates from US cost(Birrell 2012); capacity is limited by the residue output of the combine harvester.

[2] The extra cost for maize (grain) harvest due to the reduced harvest capacity are allocated to the residue harvest cost, see 4.5.3.3 for the methodology. [3] Adapted from (Department of agriculture forestry and fisheries. Republic of South Africa 2010). Capacity calculated from a loading capacity of 114m3 equal to 5,47 tonne stover (density: 48kg/m^3), a combine output of 27 tonne stover/h, an avaerge one way distance from farm to field of 0,9km at a speed of 20km/h and allowing for 5min to couple/uncouple the trailers.

Machinery	kW	Capacity (tonne/h)	Life (h)	Annual usage (h)	Purchase price ($)	lifetime (yr)	Annuity factor	Investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
10% reduced combine capacity[1]								**4,3**	**1,7**	**1,1**	**0,0**	**0,7**	**7,8**	**0,43**
Square baler (1,2mx0,9mx2,4m)[2]	124	9	3000	500	120.053	6	0,21	**5,9**	**3,5**	**0,0**	**0,0**	**0,9**	**10,3**	**0,57**
Square bale mover/stacker[3]	229	28	2500	500	1.353.996	5	0,25	**3,2**	**2,5**	**2,3**	**0,0**	**0,8**	**8,9**	**0,49**
Total								**13,3**	**7,8**	**3,4**	**0,0**	**2,5**	**27,0**	**1,48**

Table 57: Direct cost of the option to **bale the residues dropped behind the combine** harvester, thereby picking-up the residues from the ground.

[1] The extra cost for maize (grain) harvest due to the reduced harvest capacity are allocated to the residue harvest cost, see 4.5.3.3 for the methodology.

[2] Based on the Massey Ferguson 2170 large square baler; Capacity limited by the residue output of the combine harvester.

[3] Based on the Stinger 6500 square bale stacker collecting 1,2mx0,88m bales with a field efficiency of 90%(Matlack 2012)(Matlack 2012); cost based on US cost (Matlack 2012).

Type	kW	Capacity (tonne/h)	Life (h)	Annual usage (h)	Purchase price ($)	lifetime (yr)	Annuity factor	Investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
10% reduced combine capacity[1]								**8,6**	**3,4**	**2,2**	**0,0**	**1,4**	**15,6**	**0,86**
Cob harvester (self powered)[1]	86	5	2000	300	70.000	7	0,20	**9,8**	**3,9**	**5,2**	**0,0**	**1,9**	**20,9**	**1,15**
Total								**18,4**	**7,4**	**7,4**	**0,0**	**3,3**	**36,5**	**2,00**

Table 58: Direct cost of the maize cob **harvest only**.

[1] Not commercially available based on estimates for the Hilco cob collection system (Cordray 2012). Since the cart can hold up to 2,5 tonne and unloading can be done in 90 seconds by dumping the cobs in a trailer, unloading time is not accounted for.

10.2.2 Variation in cost according to the percentage of residues harvested

Table 53 and Table 54 and at Table 55 and Table 56 shows that the collection cost vary with the percentage of residues removed. It is important to note that this is not dependent on the yield. The combine harvester has a certain capacity and therefore always processes the same amount of material per hour. If for example the yield is high, the combine will move through the field slower compared to fields with lower yields.

If the combine is set to process a larger percentage of the available residue, in general combine attachment (e.g. the bale direct system) works more efficient as it can now operate closer to its full capacity. On the other hand, processing more residue than normal decreases the combine capacity to harvest grain, thereby increasing cost.

The option to use machinery with a lower capacity was also assessed, for instance to use a smaller baler for the bale direct system. However the decreased operating cost for the baler were did not weigh up to the increase in collection cost, since smaller bales are more expensive to collect.

The variation in the total direct cost of residue harvest using the bale direct system (Table 53 and Table 54) and the cost using the forage blower attachment (Table 55 and Table 56) can be used to create Figure 18. The cost of collecting 50% of the available residues using the forage blower attachment are not shown in the tables above but are used to construct the graph.

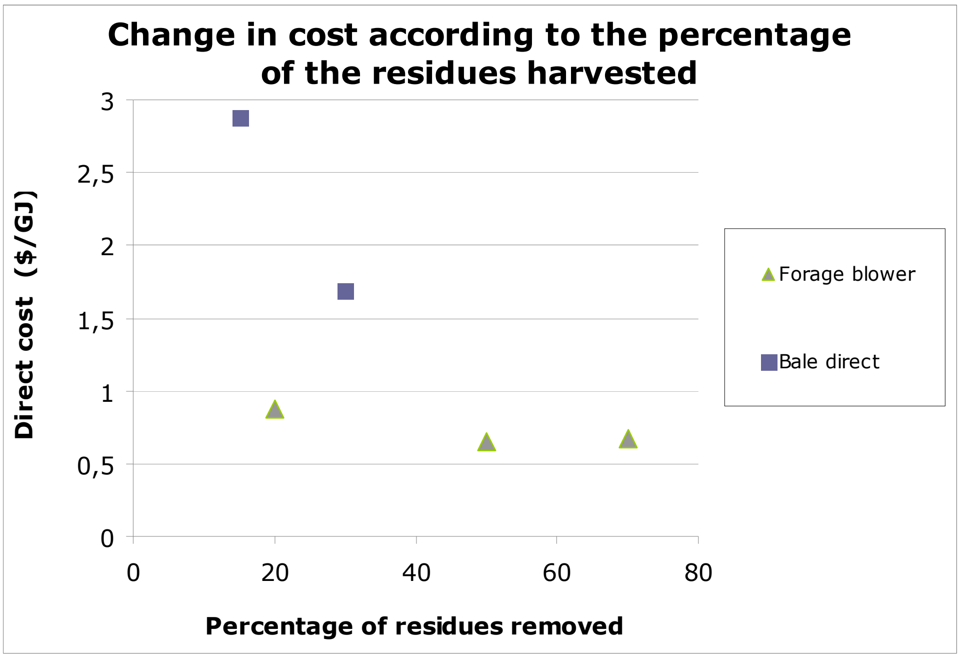

Figure 18: Relation between the direct cost of residues and the percentage of the available residues harvested using the bale direct system (see section 10.2.1.3) or a forage blower attachment (see section 10.2.1.4). Using the bale direct system, between 15% and 30% of the produced residues can be removed and using the forage blower, between 20% and 70% can be removed.

There is a striking difference between the shapes of two graphs in Figure 18. Firstly, the cost for the bale direct system (on a per tonne basis) decline when the percentage of the available residues harvested increases. Towing a heavy baler reduces that combine capacity to harvest grain. When only a small percentage of the available residue is harvested, the bale direct system as well as the baler operate well below their capacity which results in relatively high cost. When the percentage of the residues harvested increases, the material is used more efficiently, causing the costs to decline.

Harvesting residues with a forage blower attachment is a different story. As mentioned in section 10.2.1.4, about 20% of the available residues can be harvested without decreasing the capacity of the combine to harvest grain. Only when harvesting a larger percentage of the available residues, the capacity is decreased, adding cost to the residue harvest. However, as can be seen from the graph, this increase in cost is compensated by a more efficient use of the equipment resulting in lower cost.

10.2.3 Indirect cost

Since the removal of residues goes alongside with the removal of nutrients, the farmer must be compensated for these indirect costs. Table 59 Shows the (breakdown of) the nutrient compensation cost.

Nutrient	Nutrient content (tonne/tonne)	Fertilizer cost ($/tonne)	Nutrient comp. cost ($/tonne)
Nitrogen	7,18E-03	566,14	0,07
Potassium	1,28E-02	798,94	1,35
Phosphorus	2,13E-03	679,89	0,19
Total			**1,62**

Table 59: Nutrient compensation cost for the removal of maize residues. Nutrient content based on Milhollin (Milhollin et al. 2011); fertilizer cost calculated as the average over the past 5 years ((Grain South Africa 2011).

10.2.4 Total cost

An overview of the total cost, consisting of the direct and indirect cost, for the different maize stover collection methods and the corresponding collection efficiencies are shown in Table 60.

Residue harvest method	Efficiency	Direct cost ($/tonne)	Indirect cost ($/tonne)	Total cost ($/tonne)	Total cost ($/GJ)
Conventional round bale	80%	22,0	2,08	24,1	1,32
Conventional square bale	80%	22,2	2,08	24,3	1,33
Bale direct - 15%	15%	52,5	2,08	54,6	3,00
Bale direct - 30%	30%	30,7	2,08	32,8	1,80
Forage attachment 20%	20%	15,9	2,08	18,0	0,99
Forage attachement 70%	70%	12,1	2,08	14,2	0,78
Single pass: combine bale	20%	27,0	2,08	29,1	1,60
Cob harvest only	12%	36,5	2,08	38,6	2,12

Table 60: Collection efficiency, direct, indirect and total cost for the different maize stover collection methods.

10.3 Wheat

Similar to the maize harvest, the commercial wheat harvest is fully mechanized. The crop is harvested using combine harvesters, these machines cut the wheat stalks and take in the stalks with the grain attached to it (Cronje 2012). Inside the combine the grain is separated from the residual material and which is spread out behind the combine. By adjusting the cutting height of the combine, the amount of residue entering the combine can be varied. This is an important difference with the maize harvest, here the conventional header on the combine header can harvest a maximum of 30% of the available residues.

Although most new developments are taking place in the field of maize residue harvest some developments such as the 'bale direct' system are designed to handle residues from various crops. The direct cost of four different methods are discussed below.

10.3.1 Direct cost

10.3.1.1 Conventional round bale wheat straw harvest

Required field operations
Conventionally, the wheat straw harvest starts with cutting the remnants of the wheat stalks with a so called swather, which is basically a big cutter bar that cuts the stalks and gathers the material in a windrow. This windrow is picked up by a large round baler producing bales with a diameter of 1.8m. Similar to the maize residue bales, the bales are picked up by a tractor pulled flatbed with a loading arm and subsequently stacked at the field edge using a tractor mounted bale handler (see section 10.2.1.1).

Collection efficiency
The collection efficiency is assumed to be 80%, the same as the conventional collection of maize residues (See section 10.2.1.1).

The results are shown in Table 61.

10.3.1.2 Conventional square bale wheat straw harvest

Required field operations
Identical to the conventional round bale harvest, the residues are cut and windrowed using a swather. This time the windrow is picked up by a big square baler producing 1.3mx1.2mx2.4m bales. Similar to the collection of the maize residue bales, the collection is most efficient using a collector that picks up the bales and stack them on a tilted flatbed which produces vertical stacks of bales when it unloads.

Collection efficiency
The collection efficiency is assumed to be 80%, see section 10.3.1.1.

The results are shown in Table 62.

10.3.1.3 Single pass wheat straw harvest using the 'bale direct system'

Required field operations

The required field operations are the same as those described for maize, see section 10.3.1.3.

Collection efficiency
Due the design differences between maize and wheat combine headers, no special wheat header is required. Since the cutting height of the header can be varied, the amount of residues processed by the combine can also be varied. The combine can process anywhere between 20% and 70% of the available residues (Birrell 2012). This means the bale direct system can harvest between 20% and 70% of the available straw.

The results are shown in Table 63 (collecting 20%) and Table 64 (collecting 70%).

10.3.1.4 Single pass wheat straw harvest using a forage blower attachment

Required field operations
The forage blower combine attachment can be used for both maize and wheat, see section 10.2.1.4 for a description. Note that the system is not yet commercially available.

Collection efficiency
Identical to the bale direct system, between 20% and 70% of the available residues could be collected during test trials by varying the cutting height of the wheat header on the combine (Birrell 2012).

The costs are shown Table 65 (collecting 20%) and Table 66 (collecting 70%).

10.3.1.5 Bale directly behind combine (ground pick-up)

Required field operations
The spreader on the back of the combine is turned off and as a result the combine drops the residues in a windrow which is directly picked up by the baler attached to the combine. The efficiency is low compared to the other single pass harvest methods because the residues dropped by the combine get stuck between the remnants of the stalks.

Collection efficiency
This is the least efficient way of collecting wheat residues, similar to single pass maize stover harvest, the residues shredded by the combine get stuck between what is left of the wheat stalks. The collection efficiency is assumed to be the same as for maize stover, 25%.

The results are shown in Table 67.

Type	kW	Capacity (tonne/h)	Life (hr)	Annual usage (hr)	Purchase price ($)	lifetime (yr)	Annuity factor	investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
Swather (11m)[1]	63	50	2.000	200	55.208	10	0,15	**0,8**	**0,4**	**0,4**	**0,0**	**0,2**	**1,8**	**0,1**
Round baler (1,8m diameter)[2]	112	39	1.500	250	47.000	6	0,21	**1,0**	**0,9**	**0,0**	**0,0**	**0,2**	**2,1**	**0,1**
Tractor (123kW)	123		16.000	1.500	124.657	11	0,14	**0,3**	**0,2**	**0,9**	**0,0**	**0,1**	**1,6**	**0,1**
Subtotal								**1,3**	**1,2**	**0,9**	**0,0**	**0,3**	**3,7**	**0,2**
Round bale mover[3]	67	13	2.500	500	16.328	5	0,25	**0,6**	**0,5**	**0,0**	**0,0**	**0,1**	**1,3**	**0,1**
Tractor (73kW)	73		16.000	1.500	59.148	11	0,14	**0,4**	**0,3**	**1,6**	**0,0**	**0,2**	**2,7**	**0,2**
Subtotal								**1,1**	**0,9**	**1,6**	**0,0**	**0,4**	**3,9**	**0,2**
Telescopic bale handler[4]	60	52	4.000	1.000	107.670	4	0,30	**0,6**	**0,5**	**0,0**	**0,0**	**0,1**	**1,2**	**0,1**
Tractor (60kW)	60		16.000	1.500	44.669	11	0,14	**0,1**	**0,1**	**0,3**	**0,0**	**0,0**	**0,5**	**0,0**
Subtotal								**0,7**	**0,6**	**0,3**	**0,0**	**0,2**	**1,7**	**0,1**
Total								**3,9**	**3,0**	**3,2**	**0,1**	**1,0**	**11,2**	**0,6**

Table 61: Direct cost for the **conventional round bale** wheat straw harvest.

[1] Based on the Massey Furguson 9220 swather; capacity based on a forward speed of 15km/h during swathing, the 10 year avg. wheat residue yield and a field efficiency of 90%.

[2] Based on the 'Vermeer 605 Super M' baler(Ham 2012); capacity based on production of 40bales/h and a field efficiency of 90%; based on US prices

[3] Adapted from Sokhansanj (Sokhansanj, Turhollow 2002). Capacity in tonne/h based on the capacity of 11,7 bales/h which is calculated using a bale collection rate of 14 bales/h, a load capacity of 14 bales, a speed of 16km/h and an avg. distance form field to farm of 0,9km and a unloading time of 5min.

[4] Adapted from Sokhansj (Sokhansanj, Turhollow 2002) Capacity calculated from a capacity of 48 bales/h and the round bale volume and density.

Type	kW	Capacity (tonne/h)	Life (hr)	Annual usage (hr)	Purchase price ($)	lifetime (yr)	Annuity factor	investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
Swather (11m)[1]	63	50	2.000	200	55.208	10	0,15	**0,8**	**0,4**	**0,4**	**0,0**	**0,2**	**1,8**	**0,10**
Square baler (1,3x1,2x2,4m)[2]	134	32	3.000	500	192.497	6	0,21	**2,5**	**1,9**	**0,0**	**0,0**	**0,4**	**4,9**	**0,27**
Tractor (136kW)	136		16.000	1.500	160.968	11	0,14	**0,5**	**0,4**	**1,2**	**0,0**	**0,2**	**2,2**	**0,13**
Subtotal								**3,0**	**2,3**	**1,2**	**0,0**	**0,6**	**7,1**	**0,40**
Square bale mover/stacker[3]	229	41	2.500	500	179.100	5	0	**2,2**	**1,7**	**1,6**	**0,0**	**0,6**	**6,1**	**0,34**
Total								**6,0**	**4,5**	**3,1**	**0,0**	**1,4**	**15,0**	**0,84**

Table 62: Direct cost for the **conventional square bale** wheat straw harvest.

[1] Based on the Massey Furguson 9220 swather; capacity based on a forward speed of 15km/h during swathing, the 10 year avg. wheat residue yield and a field efficiency of 90%.

[2] Based on the Massey Furgeson 2190 baler; Capacity based on the production of 60 bales/h and a field efficiency of 90%; investment cost based on European cost.

[3] Based on the Stinger 6500 square bale stacker collecting 1,2mx1,3m bales; cost based on US cost (Matlack 2012).

Type	kW	Capacity (tonne/h)	Life (hr)	Annual usage (hr)	Purchase price ($)	lifetime (yr)	Annuity factor	investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
10% reduced combine capacity[1]								4,1	**1,6**	**1,4**	**0,0**	**5,9**	**12,9**	**0,73**
Bale direct system[2]		8	2.000	300	72.500	7	0	5,9	**2,3**	**0,0**	**0,0**	**0,8**	**9,0**	**0,51**
Square baler (1,2mx0,88mx2,4m)[3]	124	8	3.000	500	120.053	6	0	6,3	**4,7**	**0,0**	**0,0**	**1,1**	**12,2**	**0,68**
Square bale mover/stacker[4]	229	28	2.500	500	179.100	5	0	3,2	**2,5**	**2,3**	**0,0**	**0,8**	**8,9**	**0,50**
Total								**19,4**	**11,3**	**3,7**	**0,0**	**8,6**	**43,0**	**2,41**

Table 63: Direct cost of wheat straw harvest using the **bale direct** system, collecting ***15%* of the available residues**.
[1] Calculated as the extra cost per tonne maize harvested due to the reduced harvest capacity, multiplied by the ratio: (tonne maize processed/hour) / (tonne residues processed/hour). Based on a 9,1m wheat combine harvester(Department of agriculture forestry and fisheries. Republic of South Africa 2010).
[2] Not commercially available; cost estimates from US cost(Birrell 2012); capacity is limited by the residue output of the combine harvester.
[3] Based on the Massey Ferguson 2190 large square baler; Capacity limited by the residue output of the bale direct system.
[4] Based on the Stinger 6500 square bale stacker collecting 1,2mx1,28m bales with a field efficiency of 90%; cost based on US cost (Matlack 2012).

Type	kW	Capacity (tonne/h)	Life (hr)	Annual usage (hr)	Purchase price ($)	lifetime (yr)	Annuity factor	investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
10% reduced combine capacity[1]								**0,9**	**0,4**	**0,3**	**0,0**	**1,3**	**2,8**	**0,16**
Bale direct system[2]		37,8	2.000,0	300,0	72.500,0	6,7	0,2	**1,3**	**0,5**	**0,0**	**0,0**	**0,2**	**1,9**	**0,11**
Square baler (1,2mx0,88mx2,4m)[3]	124	37,8	3.000,0	500,0	120.052,8	6,0	0,2	**1,4**	**1,0**	**0,0**	**0,0**	**0,2**	**2,6**	**0,15**
Square bale mover/stacker[4]	134	27	3.000	500	192.497	6	0	**3,2**	**2,5**	**2,3**	**0,0**	**0,8**	**8,9**	**0,50**
Total								**6,7**	**4,4**	**2,6**	**0,0**	**2,5**	**16,2**	**0,91**

Table 64: Direct cost of wheat straw harvest using the **bale direct** system, collecting ***70%* of the available residues**.
[1] Calculated as the extra cost per tonne maize harvested due to the reduced harvest capacity, multiplied by the ratio: (tonne maize processed/hour) / (tonne residues processed/hour). Based on a 9,1m wheat combine harvester(Department of agriculture forestry and fisheries. Republic of South Africa 2010).
[2] Not commercially available; cost estimates from US cost(Birrell 2012); capacity is limited by the residue output of the combine harvester.
[3] Based on the Massey Ferguson 2190 large square baler; Capacity limited by the residue output of the bale direct system.
[4] Based on the Stinger 6500 square bale stacker collecting 1,2mx1,28m bales with a field efficiency of 90%; cost based on US cost (Matlack 2012).

Machinery	kW	Capacity (tonne/h)	Life (h)	Annual usage (h)	Purchase price ($)	lifetime (yr)	Annuity factor	Investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
forage blower attachment[1]		10,8	2.000	300	55.000	7	0,20	**3,3**	**1,3**	**0,0**	**0,0**	**0,5**	**5,1**	0,29
Sugar cane trailer (38 tonne interlink)[2]	83	8,6	8.000	1.000	56.217	8	0,17	**1,1**	**0,6**	**0,0**	**0,0**	**0,2**	**1,8**	0,10
Tractor (83, kW)	83		16.000	1.500	82.149	11	0,14	**0,9**	**0,7**	**2,7**	**0,1**	**0,4**	**4,8**	0,27
Subtotal								**2,0**	**1,3**	**2,7**	**0,1**	**0,6**	**6,6**	0,37
Total								**5,3**	**2,6**	**2,7**	**0,1**	**1,07**	**11,8**	**0,66**

Table 65: Direct cost of wheat straw harvest using a **forage blower** attachment, collecting **20% of the available residues**.
[1] Not commercially available; cost estimates from US cost(Birrell 2012); capacity is limited by the residue output of the combine harvester.
[2] Adapted from (Department of agriculture forestry and fisheries. Republic of South Africa 2010). Capacity calculated from a loading capacity of 114m3 equal to 5,47 tonne stover (density: 48kg/m^3), a combine output of 11 tonne stover/h, an average one way distance from farm to field of 0,9km at a speed of 20km/h and allowing for 5min to couple/uncouple the trailers.

Machinery	kW	Capacity (tonne/h)	Life (h)	Annual usage (h)	Purchase price ($)	lifetime (yr)	Annuity factor	Investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
forage blower attachment[1]		37,8	2.000	300	55.000	7	0,20	**1,0**	**0,4**	**0,0**	**0,0**	**0,1**	**1,5**	0,08
20% reduced combine capacity[2]								**2,0**	**0,8**	**0,7**	**0,0**	**1,4**	**4,9**	0,27
Subtotal		37,8	2.000	300	55.000	7		2,9	1,2	0,7	0,0	1,6	6,3	0,36
Sugar cane trailer (38 tonne interlink)[3]	83	20,0	8.000	1.000	56.217	8	0,17	**0,5**	**0,2**	**0,0**	**0,0**	**0,1**	**0,8**	0,04
Tractor (83, kW)	83	0,0	16.000	1.500	82.149	11	0,14	**0,4**	**0,3**	**1,2**	**0,0**	**0,2**	**2,1**	0,12
Subtotal								**0,9**	**0,5**	**1,2**	**0,0**	**0,3**	**2,9**	0,16
Total								**3,8**	**1,7**	**1,8**	**0,0**	**1,8**	**9,19**	**0,52**

Table 66: Direct cost of wheat straw harvest using a **forage blower** attachment, collecting **70% of the available residues**.
[1] Not commercially available; cost estimates from US cost(Birrell 2012); capacity is limited by the residue output of the combine harvester.
[2] The extra cost for maize (grain) harvest due to the reduced harvest capacity are allocated to the residue harvest cost, see 4.5.3.3 for the methodology.
[3] Adapted from (Department of agriculture forestry and fisheries. Republic of South Africa 2010). Capacity calculated from a loading capacity of 114m3 equal to 5,47 tonne stover (density: 48kg/m^3), a combine output of 38 tonne stover/h, an avaerge one way distance from farm to field of 0,9km at a speed of 20km/h and allowing for 5min to couple/uncouple the trailers.

Type	kW	Capacity (tonne/h)	Life (hr)	Annual usage (hr)	Purchase price ($)	lifetime (yr)	Annuity factor	investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
10% reduced combine capacity[1]								**2,0**	**0,8**	**0,7**	**0,0**	**2,9**	**6,5**	**0,36**
Square baler (1,2mx0,9mx2,4m)[2]	124	12	3.000	500	120.053	6	0,21	**4,2**	**3,2**	**0,0**	**0,0**	**0,7**	**8,1**	**0,46**
Square bale mover/stacker[3]	229	28	2.500	500	179.100	5	0,25	**3,2**	**2,5**	**2,3**	**0,0**	**0,8**	**8,9**	**0,50**
Total								**9,4**	**6,5**	**3,0**	**0,0**	**4,5**	**23,5**	**1,32**

Table 67: Direct cost of the option to bale **the residues dropped behind the combine harvester**, thereby picking up the residues from the ground.
[1] Calculated as the extra cost per tonne maize harvested due to the reduced harvest capacity, multiplied by the ratio: (tonne maize processed/hour) / (tonne residues processed/hour). Based on a 9,1m wheat combine harvester(Department of agriculture forestry and fisheries. Republic of South Africa 2010).
[2] Based on the Massey Furgeson 2170 baler; capacity based the same as (but not limited by) the combine capacity; investment cost based on European cost.
[3] Based on the Stinger 6500 square bale stacker collecting 1,2mx0,88m bales with a field efficiency of 90%(Matlack 2012)(Matlack 2012); cost based on US cost (Matlack 2012).

10.3.2 Variation in cost according to the percentage of the available residues harvested

For the explanation why the collection cost vary for with the percentage of the residues removed and not with yield, see section 10.2.2.

The costs for removing a varying percentage of the residues using the bale direct system (Table 63 and Table 64) or the forage blower attachment (Table 65 and Table 66) are plotted in **Figure 19**.

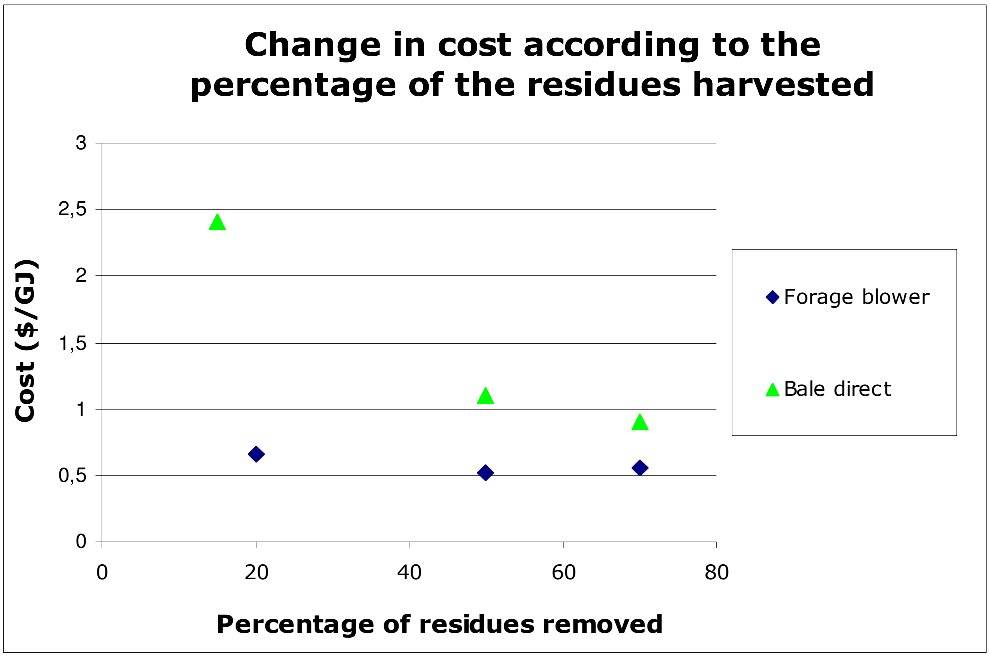

Figure 19: Relation between the direct cost of residues and the percentage of the available residues harvested using the bale direct system (see section 10.3.1.3.) or a forage blower attachment (see section10.3.1.4). Using the bale direct system, between 15% and 70% of the produced residues can be removed and using the forage blower, between 20% and 70% can be removed.

For an explanation of the different shapes of the curves for the bale direct system and the forage blower attachment, see section 10.2.2.

10.3.3 Indirect cost

The indirect cost, resulting from the nutrient loss a farmer experiences are shown in Table 68.

Nutrient	Nutrient content (tonne/tonne)	Fertilizer cost ($/tonne)	Nutrient comp. cost ($/tonne)
Nitrogen	4,99E-03	566	0,37
Potassium	9,07E-03	799	0,96
Phosphorus	1,36E-03	680	0,12
Total			**1,45**

Table 68: Nutrient compensation cost for wheat residues. Nutrient content based on Mullen (Mullen, Diedrick 2010); fertilizer cost calculated as the average over the past 5 years ((Grain South Africa 2011).

10.3.4 Total cost at farm gate

The total costs are easily calculated by adding the direct and indirect cost, the result for each harvest method and its collection efficiency is shown in **Table 69**.

Residue harvest method	Efficiency	Direct cost ($/tonne)	Indirect cost ($/tonne)	Total cost ($/tonne)	Total ($/GJ)
Conventional round bale	80%	11,2	1,45	12,6	0,71
Conventional square bale	80%	15,0	1,45	16,4	0,92
Bale direct - 15%	15%	43,0	1,45	44,5	2,49
Bale direct - 70%	70%	19,7	1,45	21,1	1,18
Forage attachment - 20%	20%	11,8	1,45	13,2	0,74
Forage attachment - 70%	70%	9,2	1,45	10,6	0,60
Single pass: combine bale	40%	23,5	1,45	24,9	1,40

Table 69: Collection efficiency, direct, indirect and total cost for the different wheat straw collection methods.

10.4 Sugar cane residues

The Sugar cane harvest is quite different from the maize and wheat residues and harvesting tops and trash is not current practice. Approximately 50% (REF) of all sugar cane is still done by burning the fields, as this makes harvesting much easier and enables manual harvest which is cheap (Euler 2010). The fire burns all the leaves without harming the stalks or roots, hence there are no harvest residues. The other 50% is harvested mechanically. A sugar cane combine harvester cuts the stalk at the base and cuts of the top, then strips of the leaves, cuts the stalks in pieces and blows them into a trailer travelling alongside. The residues are blown out from the back of the combine.

Most attention goes out to sugar cane bagasse and very little has been done on efficient harvest of sugar cane tops and trash. There have been some small scale trials on harvesting both the stalks and the tops and trash simultaneously but nothing substantial up till now. The only option left is to rake and bale the tops and trash left after mechanical harvest, the direct cost associated with this method are discussed below.

10.4.1 Direct cost

10.4.1.1 Conventional round bale sugar cane tops and trash harvest

Required field operations
Opposed to the maize and wheat resiudes, there is no need to cut the residues left in the field after sugar cane harvest since everything is already cut. The residues do need to be raked as they are spread out over the entire field. After raking the residues into a windrow, the residues can be picked up by a round baler, producing bales with a 1.8m diameter. These bales are transported to the edge of the field using the round bale collector previously described in section 10.2.1.1.

Collection efficiency
The collection efficiency is assumed to be 80%, similar to the collection efficiency of conventional maize and wheat residue harvest since the methods are much alike.

10.4.1.2 Conventional square bale sugar cane tops and trash harvest

Required field operations
Again, a finger wheel rake is used to gather the residues in windrows which are subsequently picked up by a square baler producing 1.3mx1.2mx2.4m bales. These bales are collected and stack as described in section 10.2.1.2.

Collection efficiency
Similar to the conventional round bale sugar cane tops and trash harvest, the collection efficiency is 80%.

Machinery	kW	Capacity (tonne/h)	Life (h)	Annual usage (h)	Purchase price ($)	lifetime (yr)	Annuity factor	Investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
Finger wheel rake[1]	33	26	2500	200	7033	13	0,13	**0,2**	**0,1**	**0,0**	**0,0**	**0,0**	**0,3**	**0,02**
Tractor (35kW)	35	0	16000	1500	29428	11	0,14	**0,1**	**0,1**	**0,4**	**0,0**	**0,1**	**0,7**	**0,04**
Subtotal								**0,3**	**0,2**	**0,4**	**0,0**	**0,1**	**1,0**	**0,06**
Round baler (1,8m diameter)[2]	112	39	1500	250	47000	6	0,21	**1,0**	**0,9**	**0,0**	**0,0**	**0,2**	**2,1**	**0,13**
Tractor (123kW)	123	0	16000	1500	124657	11	0,14	**0,3**	**0,2**	**0,9**	**0,0**	**0,1**	**1,6**	**0,09**
Subtotal								**1,3**	**1,2**	**0,9**	**0,0**	**0,3**	**3,7**	**0,22**
Round bale mover[3]	67	14	2500	500	16328	5	0,25	**0,6**	**0,6**	**0,0**	**0,0**	**0,1**	**1,3**	**0,08**
Tractor (67kW)	73	0	16000	1500	59148	11	0,14	**0,4**	**0,3**	**1,5**	**0,0**	**0,2**	**2,5**	**0,15**
Subtotal								**1,0**	**0,9**	**1,5**	**0,0**	**0,3**	**3,8**	**0,23**
Telescopic bale handler[4]	60	52	4000	1000	107670	4	0,30	**0,6**	**0,5**	**0,0**	**0,0**	**0,1**	**1,2**	**0,07**
tractor (60kW)	60	0	16000	1500	44669	11	0,14	**0,1**	**0,1**	**0,3**	**0,0**	**0,0**	**0,5**	**0,03**
Subtotal								**0,7**	**0,6**	**0,3**	**0,0**	**0,2**	**1,7**	**0,10**
Total								**3,3**	**2,8**	**3,1**	**0,1**	**0,93**	**10,2**	**0,61**

Table 70: Direct cost of **conventional round bale** sugar cane tops and trash harvest.
[1] Capacity in ha/h based on liner extrapolation of the capacity of a 6m rake(Department of agriculture forestry and fisheries. Republic of South Africa 2010), capacity in tonne/h calculated using the the 10 year average stover yield.
[2] Based on the 'Vermeer 605 Super M' baler(Ham 2012); capacity based on production of 40 bales/h and a field efficiency of 90%; cost based on US prices
[3] Adapted from Sokhansanj (Sokhansanj, Turhollow 2002). Capacity in tonne/h based on the capacity of 11,7 bales/h which is calculated using a bale collection rate of 14 bales/h, a load capacity of 14 bales, a speed of 16km/h and an avg. distance form field to farm of 0,9km and a unloading time of 5min.
[4] Adapted from Sokhansj (Sokhansanj, Turhollow 2002) Capacity calculated from a capacity of 48 bales/h and the round bale volume and density.

Machinery	kW	Capacity (tonne/h)	Life (h)	Annual usage (h)	Purchase price ($)	lifetime (yr)	Annuity factor	Investment ($/tonne)	R&M ($/tonne)	F&L cost ($/tonne)	Labor ($/tonne)	Profit ($/tonne)	Total ($/tonne)	Total ($/GJ)
Finger wheel rake[1]	33	26	2.500	200	7.033	13	0,13	**0,2**	**0,1**	**0,0**	**0,0**	**0,0**	**0,3**	**0,02**
Tractor (35kW)	35	0	16.000	1.500	29.428	11	0,14	**0,1**	**0,1**	**0,4**	**0,0**	**0,1**	**0,7**	**0,04**
Subtotal								**0,3**	**0,2**	**0,4**	**0,0**	**0,1**	**1,0**	**0,06**
Square baler (1,3mx1,2mx2,4x)[2]	134	32	3.000	500	192.497	6	0,21	**2,5**	**1,9**	**0,0**	**0,0**	**0,4**	**4,9**	**0,29**
Tractor (136kW)	136	0	16.000	1.500	160.968	11	0,14	**0,5**	**0,4**	**1,2**	**0,0**	**0,2**	**2,2**	**0,13**
Subtotal								**3,0**	**2,3**	**1,2**	**0,0**	**0,6**	**7,1**	**0,43**
Square bale mover/stacker[3]	229	41	2.500	500	179.100	5	0	**2,2**	**1,7**	**1,6**	**0,0**	**0,6**	**6,1**	**0,37**
Total								**5,5**	**4,2**	**3,2**	**0,1**	**1,3**	**14,2**	**0,85**

Table 71: Direct cost of **conventional square bale** sugar cane tops and trash harvest.
[1] Capacity in ha/h based on liner extrapolation of the capacity of a 6m rake(Department of agriculture forestry and fisheries. Republic of South Africa 2010), capacity in tonne/h calculated using the the 10 year average stover yield.
[2] Based on the Massey Furgeson 2190 baler; Capacity based on the production of 60 bales/h and a field efficiency of 90%; investment cost based on European cost.
[3]Based on the Stinger 6500 square bale stacker collecting 1,2mx1,3m bales(Matlack 2012)(Matlack 2012); cost based on US cost (Matlack 2012).

10.4.2 Relation between supply cost and fraction

There is no relation between the cost of residues and the supply.

10.4.3 Indirect cost

The Nutrients removed with every tonne of sugar cane trash and the compensation costs for this nutrient loss are shown in Table 72.

Nutrient	Nutrient content (tonne/tonne)	Fertilizer cost ($/tonne)	Nutrient comp. cost ($/tonne)
Nitrogen	4,20E-03	566	0,31
Potassium	5,70E-03	799	0,60
Phosphorus	1,50E-03	680	0,13
Total			**1,05**

Table 72: Nutrient compensation cost for sugar cane trash. Nutrient content based on Yadav (Yadav, Singh & Srivastava 1987); fertilizer cost calculated as the average over the past 5 years ((Grain South Africa 2011).

10.4.4 Total cost

Table 73 summarizes the direct, indirect as well as the cost and the collection efficiency of the previously discussed sugar cane trash collection methods.

Residue harvest method	Collection efficiency	Direct cost ($/tonne)	Ind. cost ($/tonne)	Total cost ($/tonne)	Total ($/GJ)
Conventional round bale	80%	10	1,05	11,2	**0,67**
Conventional square bale	80%	14	1,05	15,2	**0,91**

Table 73: Collection efficiency, direct, indirect and total cost for the different sugar cane trash collection methods.

10.5 Transport cost

Since the different harvest methods described in the sections above deliver the residues in different forms, it is not possible to make a fair comparison yet. Most methods produce bales while with others the residues end up loose in a trailer. To allow for a fair comparison it is necessary to assess the transport cost of the bales as well as the loose material. Since the density of even baled residues is rather low, the transport is volume constraint and not weight constraint and thus the transport cost for the loose material is higher.

The transport costs per truck/km are typically fixed, assuming loading and unloading times can be neglected. The typical price for bulk road transport in South Africa is 1 R/tonne/km assuming a full load (in terms of weight) (Axer 2012, van Griethuysen 2012). Regarding a truck with a 28 tonne capacity this equals 3.7 $/km per truck, see Table 74.

Before bales can be transported they have to be loaded use a bale handler. These handling costs were calculated to be max. 0.28$/tonne, since this is less than the transport cost for one kilometer it was decided not to include them.

Assumptions	Value	Unit	Reference
Load capacity truck	90	m^3	Euler, 2010
Load capacity truck	28	tonne	Euler, 2010
Transport cost (per truck)[1]	4,5	$/(km*truck)	Axer, 2012 and van Griethuysen 2012
Square bale volume (1,3mx1,2mx2,4m)	3,7	m^3	Massey Ferguson, 2012
Square bale volume (1,2mx0,9mx2,4m)	2,5	m^3	Massey Ferguson, 2012
Round bale volume (1,8m diameter)[2]	5,2	m^3	Vermeer, 2012
Square bale weight (1,3mx1,2mx2,4m)	0,6	tonne	Grigson 2012
Square bale weight (1,2mx0,9mx2,4m)	0,4	tonne	Grigson 2012
Round bale weight (1,8m diameter)	1,1	tonne	Vermeer, 2012
Unbaled stover density	$4,8 * 10^{-2}$	tonne/m^3	Birrell, 2012
Maize cobs density[3]	13,5	tonne/m^3	Cordray, 2012

Table 74: Assumptions used for the calculations of the transport costs.
[1] Based on 1 R/(tonne*km), the price for a truck with a full load.
[2] Volume calculated as if the bale was square.
[3] Rough estimate.

With the values from Table 74 the cost in $/(tonne*km) for baled as well as unbaled residues can be calculated, the results are shown in Table 75. The results also be depicted in a graph showing the increase in cost per tonne as a function of transport distance, see Figure 20. In anyway, it is clear that the transport cost for loose residue is roughly 2.5 to 3 times more expensive than baled transport on a per kilometer basis, depending on whether the bales are square or round.

Bale transport	Bales per truck	Weight per truck (tonne)	Cost $/(tonne*km)
Square bale (1,2mx0,9mx2,4m)	35	14,4	0,31
Square bale (1,3mx1,2mx2,4m)	24	14,4	0,31
Round bale (1,8m diameter)	17	18,5	0,24
Ubaled residue transport	-	5,74	0,78
Maize cob transport	-	13,5	0,33

Table 75: Cost in $/(tonne*km) for baled and unbaled residues, dependent on the density of the residue load. Cost based on fixed cost per truck of 3.7 $/(km).

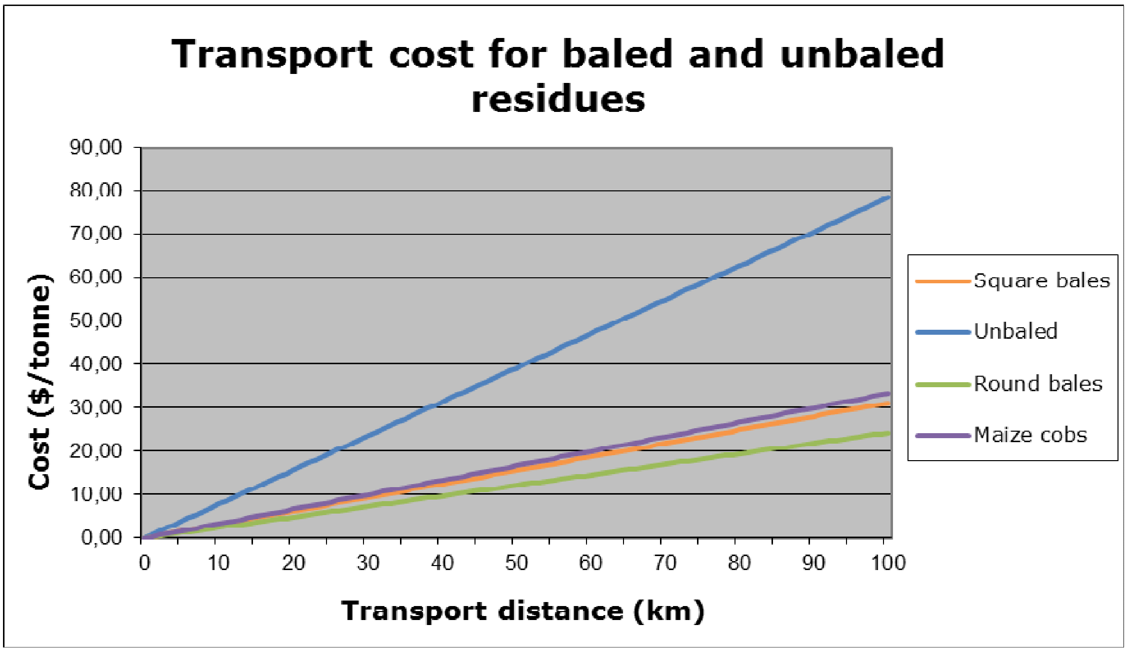

Figure 20: Transport cost as a function of transport distance for baled and unbaled residues as well as for maize cobs. Truck loading costs are not taken into account as these are less than the transport cost for 1 km.

Figure 20 shows the cost in per tonne instead of per GJ as that would result in a different curve for each residue type and would thus would complicate the picture unnecessarily. See section 10.6.2 for a cost comparison between the different residue harvest methods.

10.6 Conclusion and discussion

10.6.1 Qualitative comparison of harvest methods

Ash content
With regard to the quality of the residues collected, the conventional harvest methods are unfavorable. Due to the many field operations the residues are contaminated with a substantial amount of sand and dust. As a result, the residues generally have an ash content of 10%, with a very high standard deviation around this value. The ash content of individual samples can be as high as 25% (Birrell 2012).

Residue harvest with either the bale direct system, the forage blower attachment, or the cob harvester has a large advantage. The residues are collected directly without letting them touch the ground where they get contaminated with sand and dust. As a result the ash content is typically only 4% with a low standard deviation around this value (Birrell 2012).

Sustainability
Concerning the sustainability, chapter 9 concluded that a residue cover of 2 tonne/ha is required for erosion control and possibly a, variable, additional amount to maintain healthy SOC levels. This favors harvest methods that allow the farmer to choose what percentage of the residues he wants to harvest based on the crop yield. This is only possible when using the bale direct system or the forage blower attachment. The cob only harvest is also a good option as it only removes 12% of the produced residues.

Overall
From the above it is concluded that the new residue collection methods aiming to harvest both the main produce and a fraction of the residues in one pass are favorable compared to the conventional harvest methods. The main reasons are the much lower ash content of the delivered residues; moreover it is possible to harvest only so much residues that enough is left to meet sustainability criteria.

10.6.2 Cost based comparison of harvest methods

Cost indications based on the sustainable potential
Table 76 shows that the most cost effective way to supply **maize stover** at farm gate is by harvesting it using a forage blower attachment. Since in South Africa roughly 50% of the produced residues can be removed sustainably, Figure 18 shows that the total resulting cost are about 0.76 U.S.$/GJ.

The forage blower harvest method is also the most cost-effective for harvesting **wheat straw**. Since in South Africa roughly 50% of the produced wheat straw can be removed sustainably Figure 19 learns that the total cost at farm gate are about 0.60 U.S.$/GJ.

Sugar cane trash is best harvested conventionally in round bales. There are some new developments concerning sinlge pass harvest methods but not data were available to calculate cost for South Africa. The cost are 0.67 U.S.$/GJ but the problem is that harvesting the residues means harvesting 80% of the produced residues which is clearly more than what can be removed sustainably.

MAIZE							
Residue harvest method	**Collection efficiency**	**Direct cost ($/tonne)**	**Ind. cost ($/tonne)**	**Total cost ($/tonne)**	**Total cost ($/GJ)**	**Transp cost ($/tonne*km)**	**Transp cost ($/GJ*km)**
Conventional round bale	80%	22,0	2,08	24,1	**1,32**	0,24	1,33E-02
Conventional square bale	80%	22,2	2,08	24,3	**1,33**	0,31	1,71E-02
Bale direct - 15%	15%	52,5	2,08	54,6	**3,00**	0,31	1,71E-02
Bale direct - 30%	30%	30,7	2,08	32,8	**1,80**	0,31	1,71E-02
Forage attachment 20%	20%	15,9	2,08	18,0	**0,99**	0,78	4,30E-02
Forage attachement 70%	70%	12,1	2,08	14,2	**0,78**	0,78	4,30E-02
Single pass: combine bale	20%	27,0	2,08	29,1	**1,60**	0,31	1,71E-02
Cob harvest only	12%	36,5	2,08	38,6	**2,12**	0,33	1,83E-02
WHEAT							
Residue harvest method	**Collection efficiency**	**Direct cost ($/tonne)**	**Ind. cost ($/tonne)**	**Total cost ($/tonne)**	**Total ($/GJ)**	**Transp cost ($/tonne*km)**	**Transp cost ($/GJ*km)**
Conventional round bale	80%	11,2	1,45	12,6	**0,71**	0,24	1,36E-02
Conventional square bale	80%	15,0	1,45	16,4	**0,92**	0,31	1,75E-02
Bale direct - 15%	15%	43,0	1,45	44,5	**2,49**	0,31	1,75E-02
Bale direct - 70%	70%	19,7	1,45	21,1	**1,18**	0,31	1,75E-02
Forage attachment - 20%	20%	11,8	1,45	13,2	**0,74**	0,78	4,40E-02
Forage attachment - 70%	70%	9,2	1,45	10,6	**0,60**	0,78	4,40E-02
Single pass: combine bale	40%	23,5	1,45	24,9	**1,40**	0,31	1,75E-02
SUGAR CANE							
Residue harvest method	**Collection efficiency**	**Direct cost ($/tonne)**	**Ind. cost ($/tonne)**	**Total cost ($/tonne)**	**Total ($/GJ)**	**Transp cost ($/tonne*km)**	**Transp cost ($/GJ*km)**
Conventional round bale	80%	10	1,05	11,2	**0,67**	0,24	1,46E-02
Conventional square bale	80%	14	1,05	15,2	**0,91**	0,31	1,87E-02

Table 76: Overview of the total cost at farm gate and the transport cost for the different residue harvest methods for maize, sugar cane and wheat residues. Costs are given per tonne as well as per GJ (HHV).

Expected decrease in single pass harvest equipment
The innovative single pass harvest methods discussed are very new, they have been introduced in the past 5 years or are not even commercially available yet. Therefore it is reasonable to state that the cost will decrease in the future as an effect of technological learning as well as scaling effects.

Harvest method comparison including transport cost
The previous section concluded that the cheapest way to harvest maize stover and wheat straw it to do so using a forage blower. But, the transport costs of the loose material are 3 times higher than baled residues. For both the bale direct system and the cob harvest only, the opposite is true. Figure 21 and Figure 22 show the total cost of maize and wheat residues respectively as a function of transport distance. From these figures, the following can be concluded.

With regard to maize stover, if the material has te be transported less than 28-35km, the cheapest option to supply the residues is to harvest them using a forage blower attachment and to transport the loose material in large sugar cane trailers. If it has to be transported further, it is more economical to harvest the residues with the bale direct system or with the cob harvest system. Although the above mentioned ~30km's are dependent on the percentage of the residues that is removed, if it is only desirable to harvest a small percentage, residue harvest is the cheapest up to a distance of 40 km's, thereafter, cob harvest is the most economical option.

Concerning maize stover, the forage blower attachment provides the cheapest option for residue harvest only up to about 15km's. When it is desirable to harvest only a small percentage of the produced residues, the bale direct system 60km's, which is unlikely. is only cheaper when the distance to the central gathering point is more than

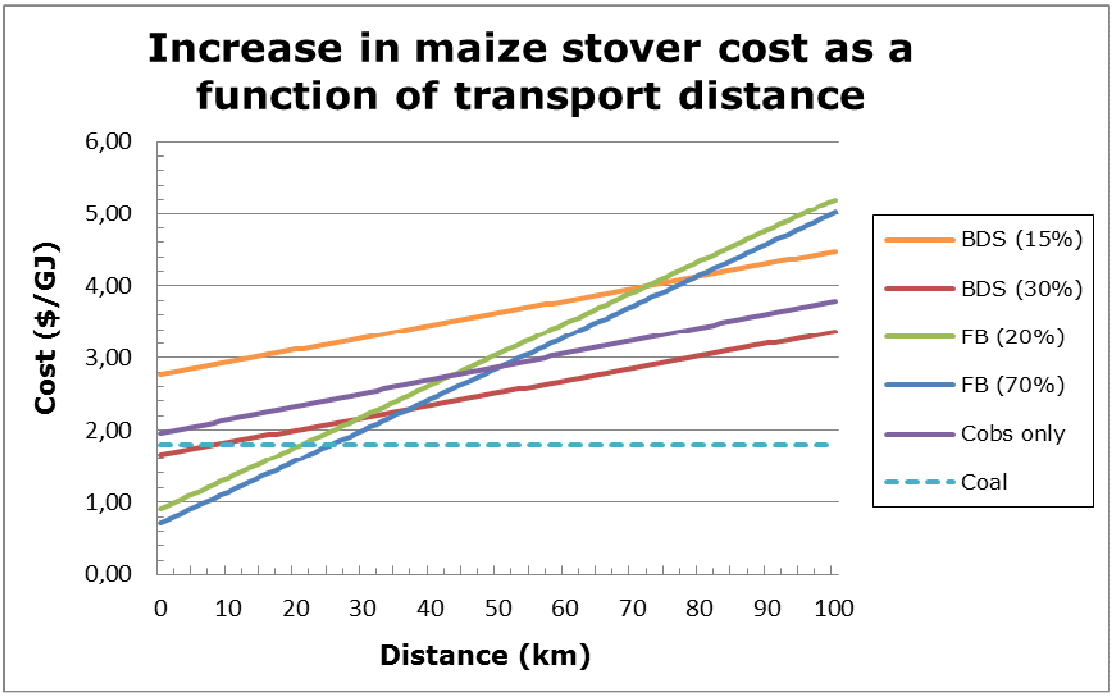

Figure 21: Increase in cost for maize stover as a function of transport distance. The cost are shown for different harvest methods, harvesting different percentages of the available residues. BDS stands for bale direct system and FB for the forage blower attachments. The cost for coal are shown as well {{116 Euler, W. 2010}}.

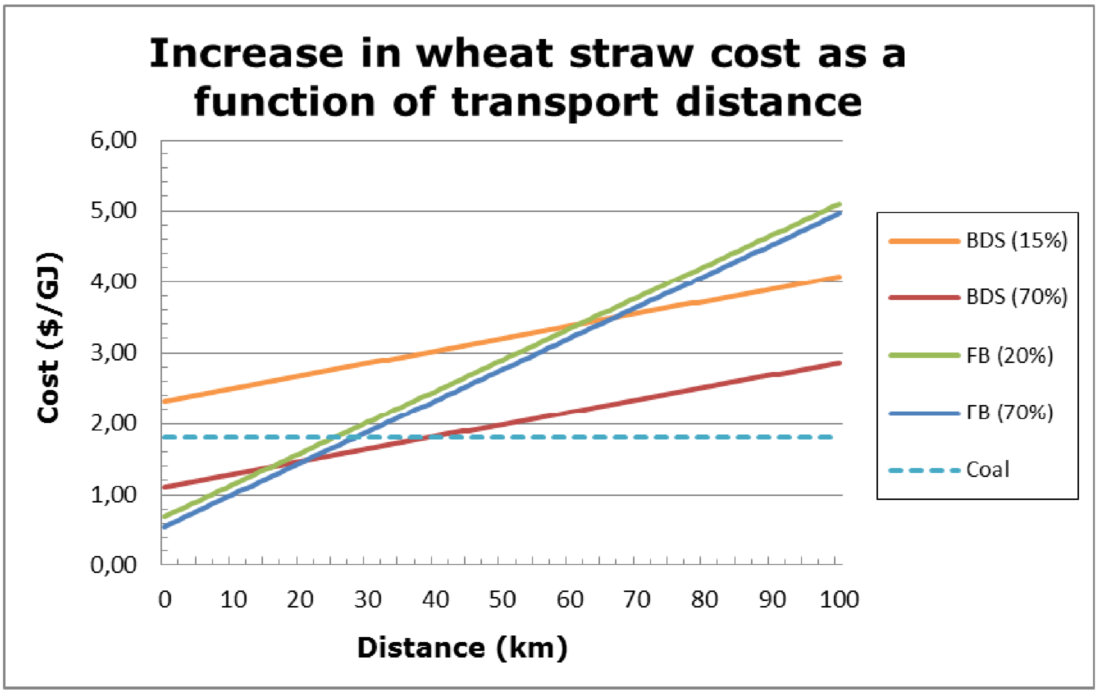

Figure 22: Increase in cost for wheat straw as a function of transport distance. The cost are shown for different harvest methods, harvesting different percentages of the available residues. BDS stands for bale direct system and FB for the forage blower attachments. The cost for coal are shown as well {{116 Euler, W. 2010}}.

Sugar cane tops and trash
The sugar tops and trash are a different story as the single pass harvest methods are not suitable. It is possible to harvest using the conventional methods although this has definite disadvantages, such as the high ash content of the residues and the fact that the option is basically to remove it all, or nothing See section 10.6.1).

On the other hand Figure 23 shows that sugar cane tops and trash harvest is potentially the cheapest option.

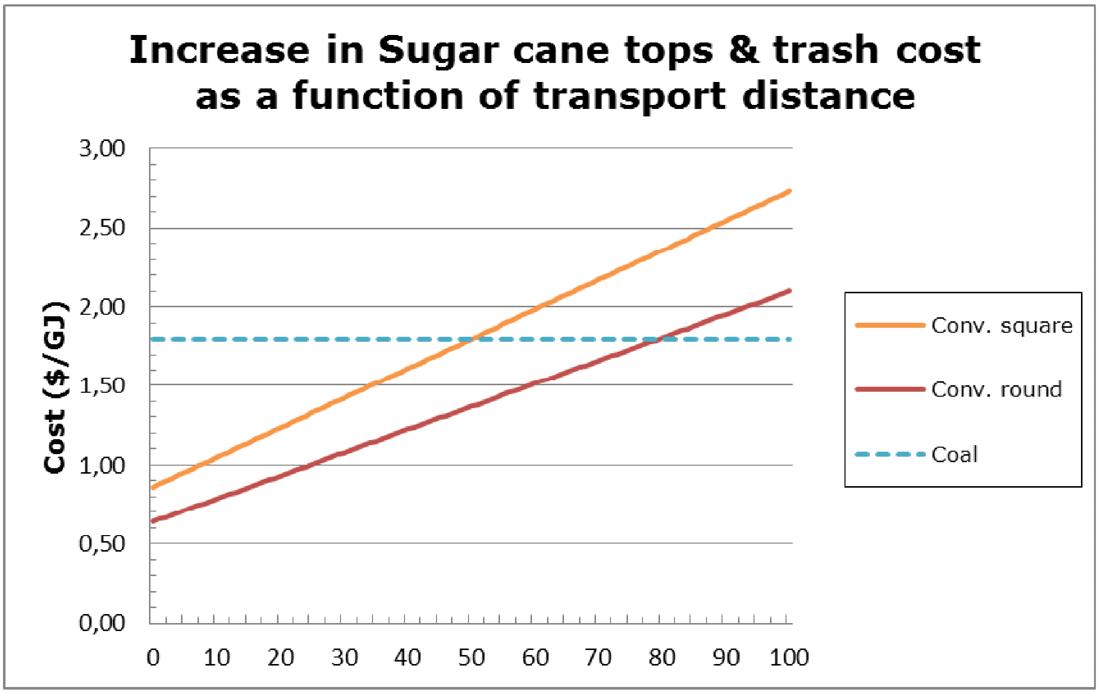

Figure 23: Increase in cost for sugar cane tops and trash as a function of transport distance. The cost are shown both conventional harvest methods, harvesting 80% of the available residues. The cost for coal are shown as well {{116 Euler, W. 2010}}.

Comparison between residues and coal/oil
If biomass is to be used for energy purposes in South Africa it wil most likely compete with coal, which fulfills 70% of the country's primary energy demand and is abundantly available at low cost (IEA 2008). Figure 21, Figure 22 and Figure 23 also show the price of coal. Taking residue transport cost into account the residue supply cost is typically higher than the coal price when the transport distance exceeds 30km's. The reverse is true for crude oil, due to the important reliance the price is about 6,5 U.S.$/GJ (Euler 2010). Then if the residues have to be transported for 50 km's they can be delivered at 3 – 4 U.S.$/GJ and add 1 – 2 U.S.$ for refining cost the feedstock can be very competitive (Hamelinck et al. 2004).

Comparison to cost to the U.S.A., Europe and Brazil
The cost are compared to the leading countries concerning residue use, being the U.S.A. for maize stover and wheat straw, Europe, for wheat straw and Brazil, for sugar cane tops and trash. First of all cost found in literature vary widely resulting from assumptions made and difference in cost components accounted for. In the U.S.A. supply cost at farm gate are estimated between 0,84 – 3,53 U.S.$/GJ for maize stover and between 1,1 and 2,9 U.S.$/GJ for wheat straw. In Europe the cost for wheat straw range from 2,0 to 5,5 U.S.$/GJ and in Brazil cost for sugar cane tops and trash range from 0,9 – 2,2 U.S.$/GJ. For all residue types the

South African cost are in the low end of these cost ranges and can even be cheaper if single pass harvest methods were introduced.

General conclusion

Cost decrease when harvesting a larger percentage of residues

In general the residue supply costs at farm gate are found to decrease when an increasing percentage of the residues is harvested, although this is only valid when harvesting residues when harvesting both the crop and the residues in a single pass. This is explained as follows. Crop and residue are harvested in one pass and a chosen percentage of the residues processed by the combine harvester is collected in this process. Thus, the capacity of the machinery harvesting the residues is determined by the residue output from the combine. In other words, if in a certain field only a low percentage of the produced residues can be harvested due to sustainability requirements, the 'residue harvesting equipment' is running below their maximum capacity, increasing cost. Using equipment with a lower capacity is found not to be cost-effective; the higher costs were mainly due to the baler, but using a smaller baler increased bale hauling cost more than it reduced baling cost. A similar relation was found by (Graham et al. 2007)

11 Sensitivity analysis

The goal of this chapter is to determine the range of possible outcomes and how the input variables determine the results.

11.1 Theoretical potential

A sensitivity analysis was performed for all factors that influence the theoretical potential, see Table 77 for the ranges used in the analysis. The variables are ranged based on values found in the literature review or possible scenarios for South Africa.

Variable	Low estimate	High estimate	Range (% change)
HHV_{dry}[1]	**16,4**	**20,0**	**90% - 110%**
Moisture content[2]	11,5	30	61% - 158%
Residue-to-product ratio[3]	0,89	1,22	83% - 114%
Yield[4]	80%	120%	80% - 120%
WHEAT			
HHV_{dry}[1]	15,7	19,1	90% - 110%
Moisture content[2]	9,2	15	77% - 115%
Residue-to-product ratio[5]	0,88	1,28	76% - 110%
Yield[4]	80%	120%	80% - 120%
SUGAR CANE TOPS AND TRASH			
HHV_{dry}[1]	15,0	18,4	90% - 110%
Moisture content[2]	59	74	88% - 110%
Residue-to-product ratio[6]	0,19	0,22	95% - 110%
Yield[4]	80%	120%	80% - 120%
SUGAR CANE BAGASSE			
HHV_{dry}[1]	17,1	20,9	90% - 110%
Moisture content[2]	46	55	92% - 110%
Residue-to-product ratio[6]	0,25	0,33	86% - 114%
Yield[4]	80%	120%	80% - 120%

Table 77: Ranges used on all factors determining the theoretical potential,
[1] Ranges as seen in literature, see Table 7.
[2] Ranges as seen in literature, see Table 8, Table 9, Table 10 and Table 11.
[3] Calculated for a low (2 tonne/ha) and high (12 tonne/ha) yield for South Africa.
[4] Variation of 20% based on 5 historical yield variations (South African Grain Information Service 2012).
[5] Calculated for a low (2 tonne/ha) and high (7 tonne/ha) yield for South Africa.
[6] Calculated for a low (50 tonne/ha) and high (70 tonne/ha) yield for South Africa.

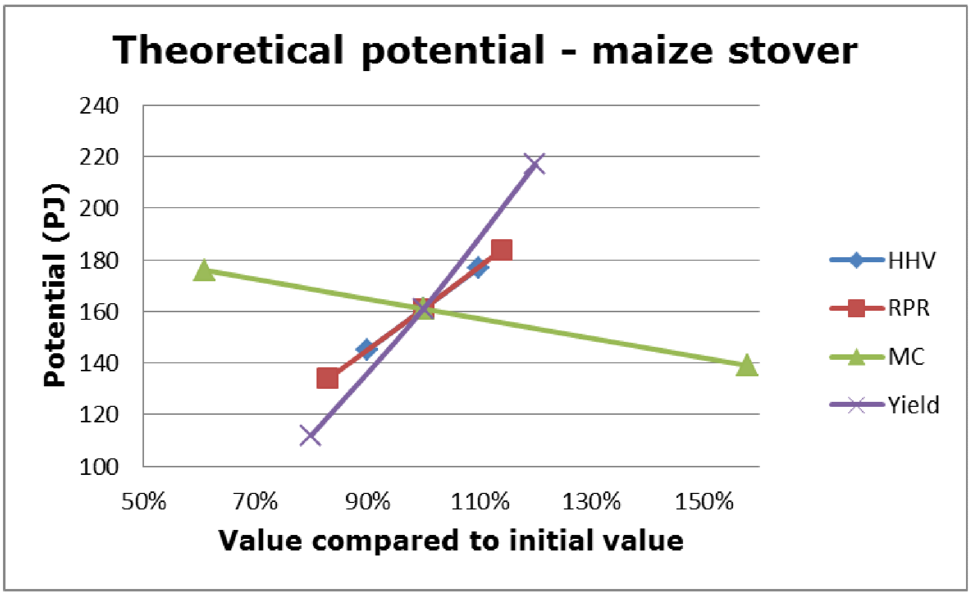

Figure 24: Sensitivity analysis on factors influencing the theoretical potential for maize stover.

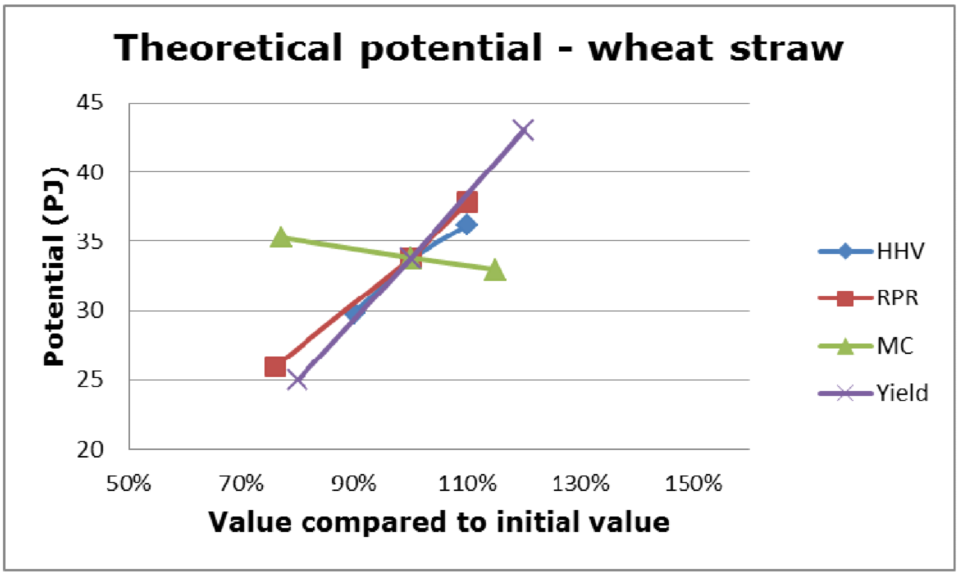

Figure 25: Sensitivity analysis on factors influencing the theoretical potential for wheat straw.

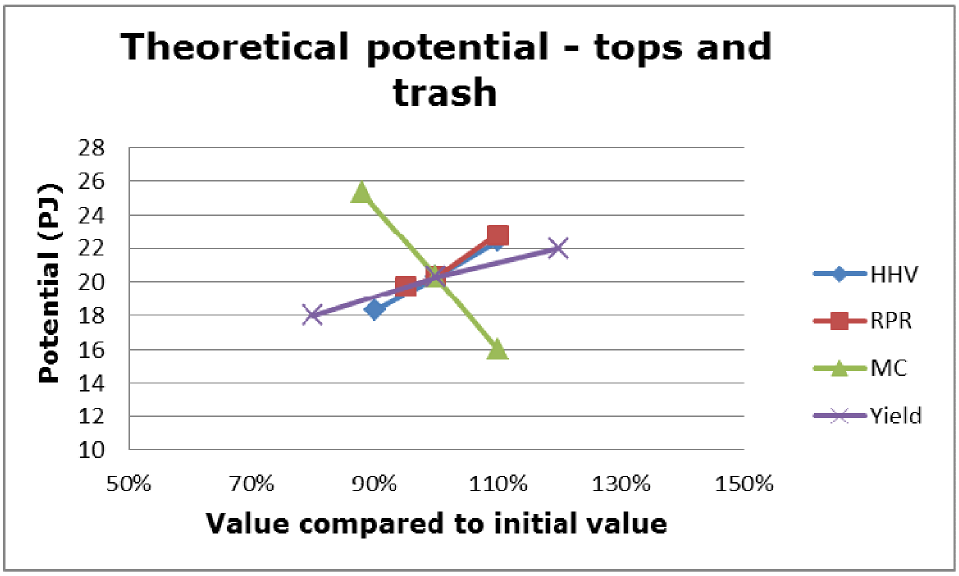

Figure 26: Sensitivity analysis on factors influencing the theoretical potential for sugar cane tops and trash.

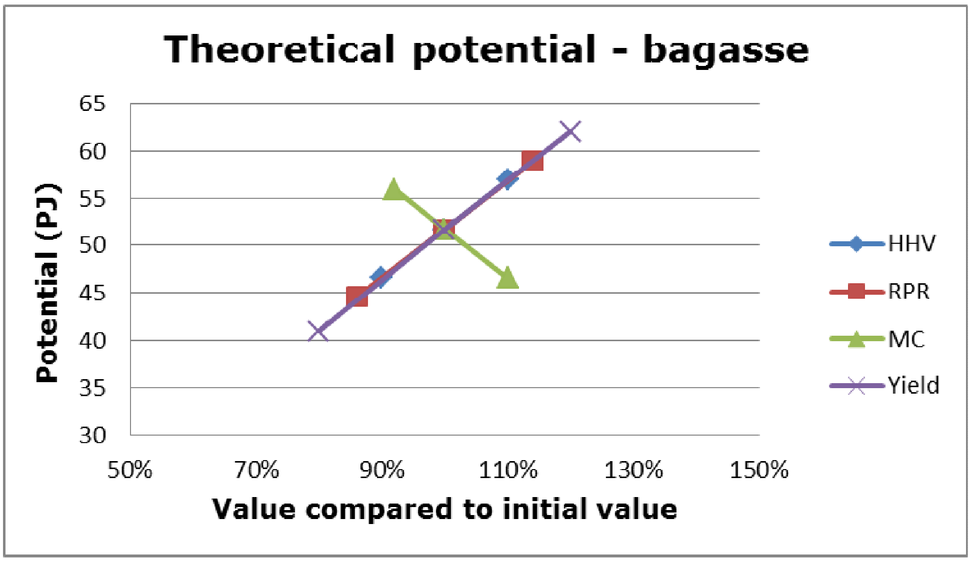

Figure 27: Sensitivity analysis on factors influencing the theoretical potential for sugar cane bagasse.

11.1.1 Conclusion theoretical potential

It is concluded that the total theoretical potential based on all four residue types can range from 194 PJ/yr to 347 PJ/yr in the worst case or best case scenario respectively. The results for maize stover and wheat straw (Figure 24 and Figure 25) are about equally sensitive for variation in the yield, RPR and HHV but clearly less sensitive to variations in the moisture content as this is generally low. The results for the tops and trash (Figure 26) on the other hand is the most sensitive to variations in the moisture content, as this is much higher compared to maize and wheat residues. Furthermore they are about equally sensitive to variations in the RPR and HHV and least sensitive to variations in the yield. At last, the results for bagasse (Figure 27) are more or less equally sensitive to all variables. The results for bagasse are more sensitive to yield variations because the RPR is fixed at 0,29 whereas for the other residues, the RPR is lower for high yields compared to low yields which levels out variations in yield.

11.2 Sustainable potential

A sensitivity analysis was performed on the selected factors as shown in Table 78. The analysis does not include the climatic inputs as these data are probably the most certain. The results are shown in Figure 28, sugar cane bagasse is obviously left out of the analysis as the sustainable potential is equal to the theoretical potential.

Variable	Low estimate	High estimate	Range (% change)
RPR below ground residues	67%	133%	67% - 133%
Depth of soil layer modelled	15 cm	30 cm	75% - 150%
Clay content of the soil	67%	133%	67% - 133%
% SOC	1,50%	2,50%	75% - 125%
Cover required for erosion control	1,5	2,5	75% - 125%

Table 78: Ranges used for the factors considered in the sensitivity analysis of the sustainable potential.
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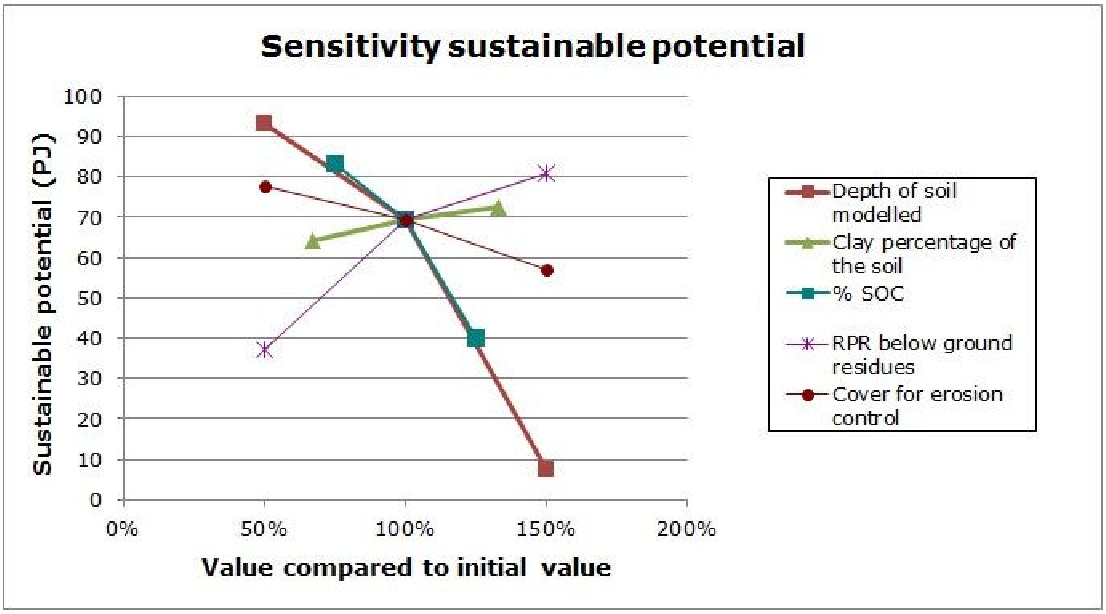

Figure 28: Sensitivity analysis on the factors determining the sustainable potential, the potential indicated is the sum of the potential from maize stover, wheat straw and sugar cane tops and trash (thus excluding bagasse since its sustainable potential is equal to its theoretical potential).

11.2.1 Discussion and conclusion sustainable potential

Ranges
It is concluded that the total sustainable potential can range from 7.4 PJ/yr to 93 PJ/yr excluding bagasse and from 59 PJ to 145 PJ including bagasse.

Three most important variables
Looking at Figure 28 it is clear that the sustainable potential is quite sensitive to changes in three variables: the depth of the soil layer modeled the percentage SOC modeled and the RPR for below ground residues. This is no surprising since the percentage of SOC and the depth of the soil layer modeled directly determine the amount of soil carbon that must be sustained. The below ground residues can

be traded against above ground residues so changes in the RPR directly change the potential

Depth of the soil layer modeled
Modeling the top 10cm. or 30cm. instead of the top 20 cm. has a dramatic effect since it can increase the sustainable potential to over 90 PJ or reduce it to practically zero. The majority of the articles only account for the top 20 cm. (or even 15 cm.) of the soil (Reicosky et al. 1995, Reicosky et al. 2002, Hooker et al. 2005). On the other hand Clapp et al. (Clapp et al. 2000) do measure changes in the top 30 cm of the soil.

Looking back at Figure 15 on page 53, two important things can be concluded. Changes in SOC take place in the top 10 – 15 cm and moreover the percentage of SOC declines with depth. Although SOC dynamics depend on local conditions, a uniform SOC level of 2% of over the top 30 cm. of soil is highly unlikely.

RPR of below ground residues
As mentioned in section 9.1.2.3 below ground residues may be more important than above ground residues as they are more efficiently converted in stable forms of SOC. However data on below ground residues is sparse as this is hard to estimate. For further discussion on data availability and uncertainty, again see section 9.1.2.3. Regarding the shape of the curve in Figure 28, a decrease in the RPR for below ground residues has a large impact whereas an increase has les influence on the results. The sustainable potential can be limited by the amount of residues required to maintain SOC levels (true for low below ground RPR’s) or by the amount of residues required to control erosion (true for high below ground RPR’s) which explains the shape of the curve (see section 9.4.1 for a discussion on the factors limiting the sustainable potential)

Percentage of SOC modeled
Increasing the SOC level modeled affects the results in the same way as changing the depth of the soil layer modeled. See section 9.1.1 for a discussion on SOC levels.

11.3 Technical potential

Considering the technical potential, a sensitivity analysis is performed on the percentage of the animals using residues and the duration of the winter period as these are both uncertain factors that had to be estimated.

Variable	Low estimate	High estimate	Range (% change)
Percentage of the population using residues	25%	75%	50% - 100%
Duration of the winter period	67%	133%	67% - 133%

Table 79: Variables considered in the sensitivity analysis of the technical potential and the ranges used for each variable.

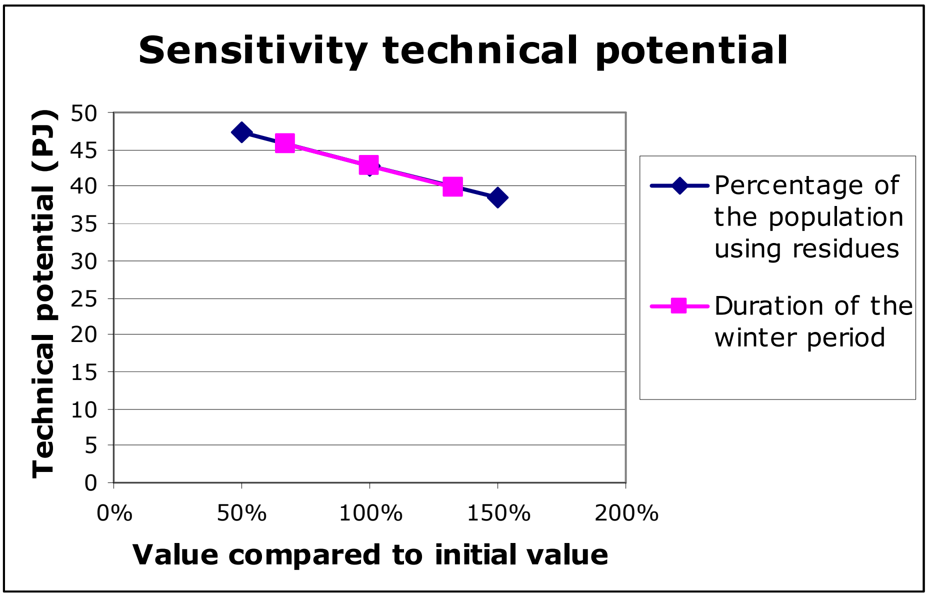

Figure 29: Sensitivity analysis on the two uncertain factors determining the total technical potential (PJ) for maize and wheat residues.

11.3.1 Conclusion technical potential

From Figure 29 it can be concluded that the technical potential for maize and wheat residues is not sensitive to changes in the percentage of the livestock population using residues and the duration of the winter period. A 50% increase or decrease changes the potential by only 10%. Sugar cane residues are not considered as their competing uses are not considered.

11.4 Supply cost

A sensitivity analysis is performed on all major assumptions underlying the supply cost, the ranges used for the different variables are shown in Table 80. Three separate analyses are performed using these ranges for the cost of all three residue types, see the figures below. Besides the obvious variables, a sensitivity analysis was performed on the investment cost of the forage blower attachment. Since this attachment is not yet commercially available, its cost are uncertain. As it is not interesting to perform the same sensitivity analysis for all residue collection methods, the analysis was only performed for the cheapest and most interesting way of collecting residues: using a forage blower attachment. Since this way of residue harvest is not suitable for sugar cane tops and trash, in this case the sensitivity analysis is performed for the option of collecting residues in large round bales.

Variable	Low estimate	High estimate	Range (% change)
Fuel price	0,56	1,7	50% - 150%
Real interest rate	5%	10%	67% - 133%
Labor cost	2,7	4,1	80% - 120%
Profit margin	5%	15%	50% - 150%
Fertilizer cost; nitrogen[1]	22,5	149,8	30% - 200%
Fertilizer cost; potassium[1]	31,7	211,4	30% - 200%
Fertilizer cost; phosphorus[1]	27,0	179,9	30% - 200%
Investment cost forage blower attachment[2]	38500	71500	70% - 130%

Table 80: Ranges used on the assumptions influencing the residue supply cost.
[1] Variation based on the variation in fertilizer cost over the past 10 years (Grain South Africa 2011).
[2] Included since the forage blower attachment is not yet commercially available and thus cost are uncertain.

The results from the analyses are depicted below.

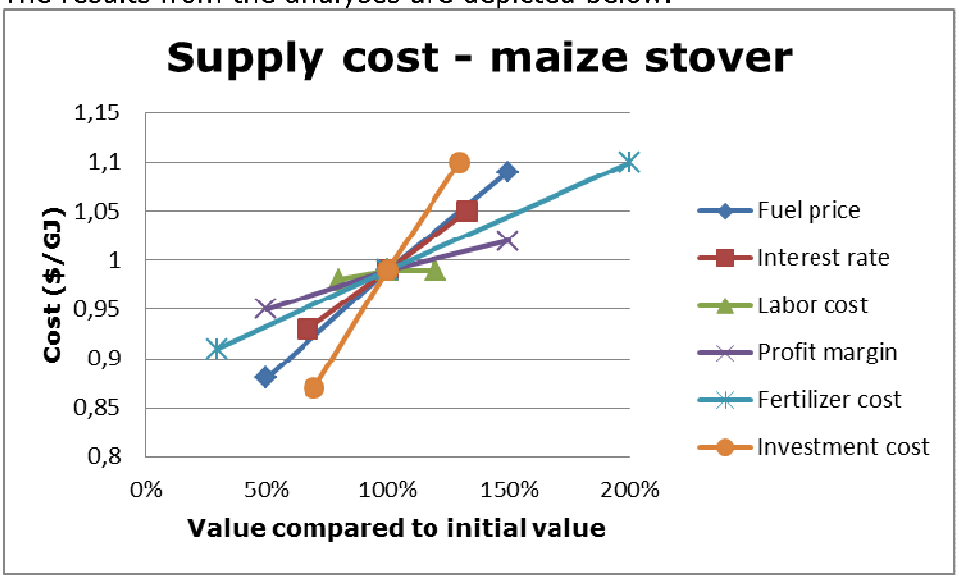

Figure 30: Sensitivity analysis on the factors influencing the supply cost of maize stover at farm gate while harvesting the residues with a forage blower attachment.

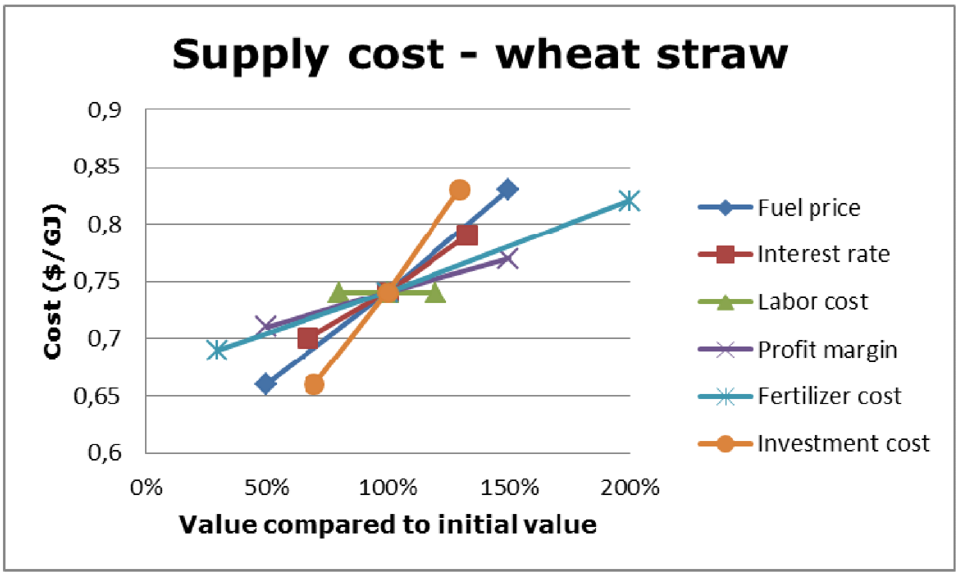

Figure 31: Sensitivity analysis on the factors influencing the supply cost for wheat straw at farm gate while harvesting the residues with a forage blower attachment.

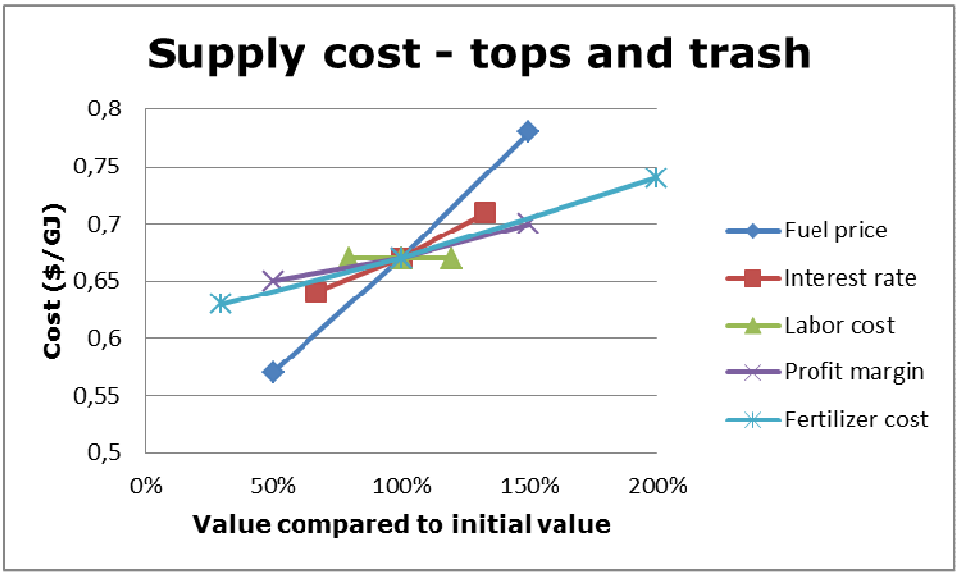

Figure 32: Sensitivity analysis on the factors influencing the supply cost for sugar cane tops and trash at farm gate while collecting the residues in large round bales.

11.4.1 Discussion and conclusion supply cost

Cost ranges

Regarding the total cost ranges it is concluded that the supply cost for residue collection using a forage blower attachment range from 0,87 $/GJ to 1,10 $/GJ for maize stover and from 0,66 $/GJ to 0,83 $/GJ for wheat residues. The cost for collecting sugar cane tops and trash in large round bales range from 0.57$/GJ to 0.78$/GJ. This means that under all conditions maize stover is the most expensive feedstock while both wheat and sugar cane tops and trash can be the cheapest, the latter being the most likely though.

Sensitivity

Generally, the supply cost are relatively insensitive to variations in the input variables and is also more or less equally sensitive to changes in the different variables. Results are the most sensitive to change in the investment cost of the forage blower attachment, a 12% change in result caused the by a 30% change of the investment cost.

Results are not sensitive to variation in the labor cost. The supply cost of maize stover and wheat straw are most sensitive to variations in the forage blower attachment cost. Furthermore they are equally sensitive to changes in the fuel price and real interest rate. Although they are a little less sensitive to changes in fertilizer cost, an increase in the fertilizer cost can thrive up the harvest cost to the maximum of the range due to the large variations observed in the past ten years.

The supply cost of sugar cane tops and trash are more or less equally sensitive to changes in interest rate and fertilizer cost but clearly the most sensitive to variations in fuel price.

12 Conclusion and discussion

This study successfully achieved the research aim to calculate residue potentials and costs for South Africa and, to understand how these potentials and costs in general are affected by the determining factors.

12.1 Theoretical potential

12.1.1 Conclusions for South Africa

The theoretical potential for bioenergy production from the considered agricultural residues is calculated to be 267 PJ. The sensitivity analysis showed that this potential can range from 194 PJ to 347 PJ based on variation in factors found in literature and conditions realistic for South Africa. This implies that the results are quite sensitive and since the sensitivity to changes the variables differed per residue type no general conclusions can be drawn.

This potential was similar to the potential calculated by the IEA (IEA 2010) although the calculation from the IEA was quite different and unrepeatable. Euler (Euler 2010) calculated a theoretical potential of 379 PJ. However, to arrive at this potential Euler assumes that with regard to maize stover and wheat straw 1 $tonne_{dry}$ residues/ha can be removed while leaving 30% of the residues in the field. This implies a RPR of 1.79 which is unrealistic compared to the average RPR of 1 assumed in literature (see section 5.1). Based on the justification it is concluded that the results from this study hold.

12.1.2 General conclusions

Relation between RPR and yield
Based on the literature review it is concluded that there is a relation between the RPR and the yield. This relation states that the RPR decreases for increasing yields and vice versa. For maize and wheat the relation presented by Scarlat (Scarlat, Blujdea & Dallemand 2011a) is picked, for sugar cane trash a relation was deducted from data available in literature and for sugar cane bagasse an average RPR 0.29 had to be assumed. An overview of the equations is shown in Table 81. The low R^2 values (0.17 – 0.29) indicate that the relations are weak and therefore must be used with caution. The weak relation is explained by the fact that the RPR also depends on the specific crop variety cultivated and the plant stresses experienced during growth.

HHV and moisture content
For both the HHV_{dry} and the moisture content averages are calculated from literature, see Table 81.

Residue type	RPR	HHV_{dry}(GJ/t)	MC (%)
Maize harvest residues	-0.1807 *ln(yield (t/ha))+1.3373	18,2	19
Wheat harvest residues	-0.3186*ln(yield (t/ha))+1.503	17,8	13
Sugar cane harvest residues	-0,097*ln(yield(t/ha))+0,5952	16,7	67
Sugar cane bagasse	0,29	19,0	50

Table 81: Summary of the RPR, HHV_{dry} and the moisture content resulting from the literature review and used throughout this study.

12.2 Sustainable and Technical potential

12.2.1 Conclusions for South Africa

Potential and uncertainty ranges
Figure 33 depicts the different potentials calculated for South Africa. The sustainable potential is 121 PJ and ranges from 59 PJ to 153 PJ, hereby the potential for bagasse I constant at 51,7 PJ which implies that in the most unfavorable scenario the potential for the harvest residues is practically reduced to zero. Finally, the technical potential is 96 PJ and ranges from 90 PJ to 99 PJ.

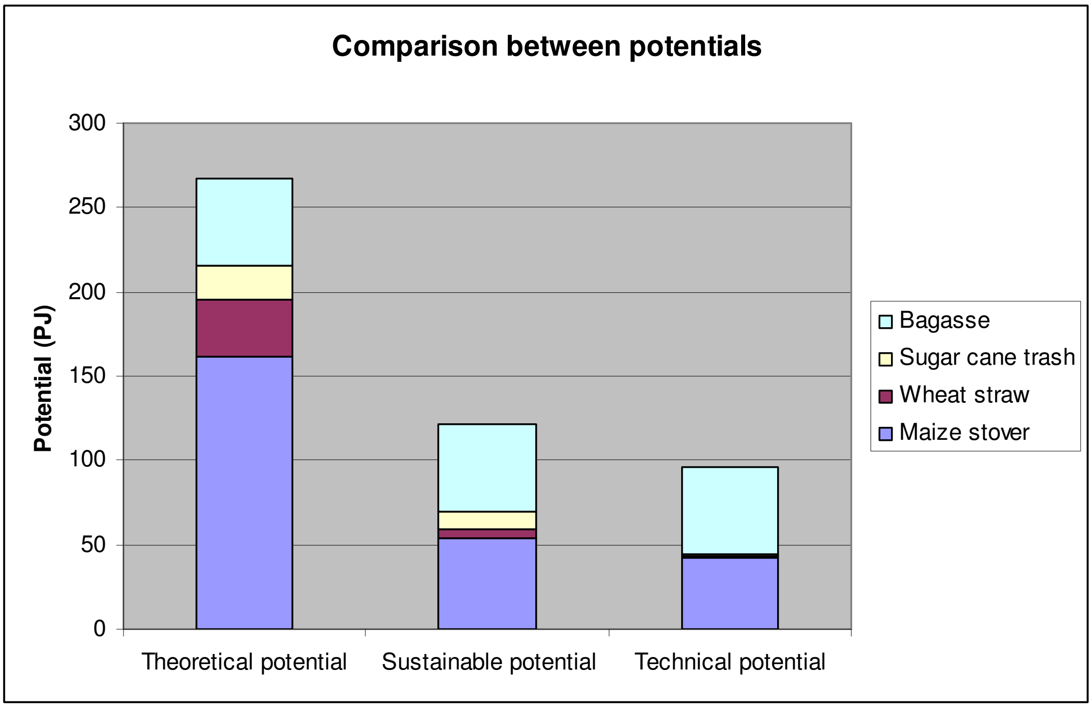

Figure 33: Comparison between the theoretical potential (267 PG), the sustainable potential (121 PJ) and the technical potential (96 PJ), showing the contribution of the different residue types to the total potentials.

Uncertainty – sustainable potential
The enormous range in the sustainable potential is explained by three factors. 1) The **depth of the soil layer modeled**. If instead of 20 cm., 30 cm, top soil is modeled the sustainable potential for harvest residues is reduced to 7 PJ. However most studies agree that a SOC mainly take place in the top 20 cm. of the soil, moreover it is clear that the SOC levels decrease with increasing depth (Reicosky et al. 1995) combined this makes a it very unlikely that a constant SOC level of 2,0% is required over 30 cm. of top soil.

2) The **percentage of the soil organic carbon**. The sustainable potential is as sensitive to changes in the soil organic carbon level modeled as to changes in the depth of the soil layer modeled since both directly determine the total amount of organic carbon that must be sustained. Although more is always better regarding SOC, a soil with a average SOC level of 2,0% over 20 cm. is considered to be of high quality, definitely since currently the many soils have SOC levels of about 0,5%. For South Africa a 2,5% SOC level is not realistic for many regions (du Preez 2012).

3) The **RPR ratio for below ground residues**. Below ground residues are probably more important in maintaining SOC than above ground residues since

they are more efficiently converted into stable forms of SOC. Since the production of below ground residues and rhizodeposition[8] in particular is hard to measure data availability is limited and the uncertainty is high.

Uncertainty – technical potential
It is apparent that the uncertainty range for the technical potential is much smaller than the range for the sustainable potential. Even if the percentage of the livestock population using residues increases from 50% to 75% the technical potential decreases by only 10%. The demand for animal uses mainly affects the wheat straw potential but this was not big to begin with.

Currently available technical potential
The technical potential (96 PJ) can contribute ~1,5% to South Africa's primary energy demand. Roughly half of the technical potential consists of bagasse and the other half consists of maize stover. All the wheat residues are required as animal bedding and virtually all the sugar cane trash is lost by open field burning prior to crop harvest. The produced bagasse is used by the sugar mills to supply their internal power demand. This can be done with about 20% - 30% (Euler 2010) of the produced bagasse with state of the art technologies but in reality this is done very inefficient since there is no market for bagasse and due to the absence of buyback rates for electricity. With the right policy in place the sugar mills could deliver electricity back to the grid.

The 42 PJ maize stover potential is dispersed from Mpumalanga to the Northern Cape. Since biomass cost increase with increasing transport distance the economical viable potential will be lower than the calculated technical potential. The 17 PJ originating from Mpumalanga can be co-fired in the coal fired power plants which are mainly located there or alternatively shipped to SASOL's coal to liquids plant in Secunda to be converted to transport fuels. Concerning the 17 PJ of maize stover available in the Free State, the best option is to co-fire it in one of the province's coal fired power plants.

Options for increasing the technical potential
There already is a trend away from burnt sugar cane harvesting (van Antwerpen et al. 2002). If **open field burning would be banned** an additional 8.5PJ of would become available. The trash can be harvested together with the cane stalks and then the sugar mills can generate additional electricity which can be delivered to the grid. Not only can this offset CO_2 emissions by replacing electricity produced by coal fired power plants, it would also prevent the CO_2 emissions resulting from the open field burning. Moreover it will improve soil quality(Nel 2011)

Another very interesting option is **double cropping**. It is calculated that growing both a summer and a winter crop in a single season reduces the required residue input by 11% - 24%. Since double cropping implies larger residue (above ground as well as below ground) yields and it is generally considered to be better if a soil is cultivated instead of bare, it is an attractive option in areas where production is not limited by water availability. Unfortunately such areas are sparse in South Africa (Steinke 2012).

[8] Rhizodeposition consists of organic compounds roots release into their surroundings during the life of a plant.

Comparison to other studies
Similar to the previous section, the calculated technical potential is compared to potentials presented by Euler (Euler 2010) and the IEA (IEA 2010).

To start with the IEA study, it assumes that 90% of the produced residues (different types alike) are used by competing uses. However no actual numbers for maize or wheat residues are provided. Regarding sugar cane trash the assumed 90% loss is similar to the 85% loss assumed in this study however the higher theoretical potential results in a technical potential that is also higher. For sugar cane bagasse the values vary widely because the IEA assess the availability for biofuel production and thus regards energy production by the sugar mills as a competing use.

Euler's study arrives at a technical potential which is almost three times higher than the result from this study. However, first of all it is based on the unrealistic assumption that 1 $tonne_{dry}$ stover can be removed per tonne of maize produced while leaving 30% of the residues in the field and second, assuming that 5% of the residues is used for competing uses based on U.S. figures. Euler also arrives at a much higher potential for sugar cane trash his number estimates the potentially available amount if open field burning was banned. The potential from bagasse is very similar to this study although the calculation method is quite different.

12.2.2 General conclusions

High yields required
The amount of residues required to maintain soil productivity is not dependent on the crop yield. This implies that in areas where high yields can be achieved the sustainable potential will be high. For South Africa the sustainable potential is about half the theoretical potential. In South Africa the yields are ~4 tonne/ha, ~3 tonne/ha and ~60 tonne/ha for maize wheat and sugar cane respectively. However in U.S.A. the average yields are ~10 tonne/ha and ~3 tonne/ha for maize and wheat respectively; Europe where the average yields are ~7 tonne/ha and ~5 tonne/ha for maize and wheat respectively and Brazil where the average sugar cane yield is ~75 tonne/ha. This quick comparison learns us that these areas where high yields are the norm can potentially provide large quantities of residues for bioenergy generation. (REF FAOSTAT).

Limiting factors – sustainable potential
The sustainable potential is affected by the amount of residues required for erosion control (2 tonne/ha) and the amount of residues required to maintain 2,0% SOC (variable). The interesting thing is that which of these two factors is limiting depends on the yield. For South Africa the residue cover required for erosion control becomes limiting when the crop yield exceeds ~4 tonne/ha for maize and wheat and ~60 tonne/ha for sugar cane. Although the thresholds will vary for different areas, the general principle, stating that for low crop yields the residues required to maintain SOC levels are limiting and for high yields the required erosion cover is limiting, holds.

For low yields the amount of below ground residues produced is also low, thus it is necessary to leave part of the above ground residues in order to maintain 2,0% SOC. In this case more than 2 tonne/ha of above ground residues is required to maintain SOC levels making this the limiting factor. On the other hand when the yield is high, the amount of below ground residues produced is almost sufficient to maintain SOC and the residue cover for erosion control is limiting. Looking at the above stated crop yields in the U.S.A., obviously this increases the theoretical potential but moreover it will decrease the gap between the theoretical and technical potential.

Animal uses
South Africa has an extensive livestock production sector and it is common practice for farmers to produce cattle additional to crops to generate some additional income. The result is that 14% of the sustainable potential is required as either feed (maize stover) or bedding (wheat straw). In other parts of the world the demand for animal uses may be smaller resulting in a higher technical potential. In the U.S.A. for example the demand for residues by for animal uses is only 5% (REF EULER).

Increasing the technical potential
Obviously the conclusion that the **banning of open field burning** is beneficial not specific for South Africa but is generally true. Globally 85% of sugar cane fields is burnt prior to harvest wasting large potentials of sugar cane trash(van Antwerpen et al. 2002). **Double cropping** is the the other option. As discussed above growing both a summer and a winter crop can decrease required residue inputs to maintain 2.0% SOC by 11% - 24% and since it also increase (above and below ground) residues yields, and is also beneficial for soil productivity, it is a win win situation.

12.3 Supply cost

12.3.1 Conclusion for South Africa

Conventinal vs single pass harvest: cost comparison

Conventionally the crop and crop harvest are separate operations. First the residues are blown back into the field by the combine harvester then these residues are cut, raked, baled (round bales are the cheapest option) and hauled to the edge of the field. The resulting cost are 1,32 U.S.$.GJ , 0,71 U.S.$.GJ and 0,67 U.S.$.GJ for maize stover, wheat straw and sugar cane trash respectively. Transport cost add an additional 0,24 U.S.$/km. These cost include a 0,11, 0,08 and 0,06 U.S.$/GJ nutrient compensation cost for stover straw and tops and trash respectively.

The cheapest option to harvest maize and wheat residues is to do so in a single pass, together with the crop main produce. The residues processed by the combine harvester are blown directly into a wagon driven alongside the combine harvester by a specially designed forage blower combine attachment. The price can be as low as 0,78 U.S. $/GJ for maize stover and 0,60 U.S. $/GJ for wheat straw (also including nutrient compensation). It is not possible to harvest sugar cane trash this way. Harvesting wheat straw is thus the cheapest option at 0,60 U.S. $/GJ apart from bagasse which is available at zero cost at the factory. The density of the loose material when blown in to the forage wagon is a major logistical problem resulting in transport cost of 0,78 U.S.$/GJ, three times the cost for bale transport.

The single pass harvest discussed above is not commercially available yet but is expected within 5 years. More innovative single pass harvest methods were assessed, at the moment the cost are still relatively high but since all these technologies are very new cost can be expected to decrease as scale and learning effects kick in.

Uncertainty

These supply cost are relatively insensitive to variations in the input variables and is also more or less equally sensitive to changes in the different variables. Results were the most sensitive to change in the investment cost of the forage blower attachment, a 12% change in result caused the by a 30% change of the investment cost.

Comparison to coal and oil

Due to its enormous resources and availability at shallow depth coal is cheap in South Africa, priced at 1,90 U.S. $/GJ (Euler 2010). Taking residue transport cost into account the residue supply cost is typically more expensive when the transport distance exceeds 30km's. The reverse is true for crude oil, due to the important reliance the price is about 6,5 U.S.$/GJ (Euler 2010). Then if the residues have to be transported for 50 km's they can be delivered at 3 – 4 U.S.$/GJ and add 1 – 2 U.S.$ for refining cost the feedstock can be very competitive (Hamelinck et al. 2004).

Comparison to cost to the U.S.A., Europe and Brazil

The cost are compared to the leading countries concerning residue use, being the U.S.A. for maize stover and wheat straw, Europe, for wheat straw and Brazil, for sugar cane tops and trash. First of all cost found in literature vary widely resulting from assumptions made and difference in cost components accounted for. In the U.S.A. supply cost at farm gate are estimated between 0,84 – 3,53 U.S.$/GJ for maize stover and between 1,1 and 2,9 U.S.$/GJ for wheat straw. In Europe the cost for wheat straw range from 2,0 to 5,5 U.S.$/GJ and in Brazil cost for sugar cane tops and trash range from 0,9 – 2,2 U.S.$/GJ. For all residue types the South African cost are in the low end of these cost ranges and can even be cheaper if single pass harvest methods were introduced.

12.3.2 General conclusions

Qualitative comparison between conventional and single pass harvest
Innovative new harvest methods that are being developed have two major benefits. First, the quality of the delivered residues is higher. Because the residues never touch they are less contamined with dirt. Compared to conventional harvest where residues are cut and raked, the ash content is on average more than 5 percent point lower. Second, the single pass harvest methods allow the farmer to choose the amount of residues he wants to remove which is not possible with conventional harvest methods, this is quite important as it is not sustainable to remove all the residues from the field.

Cost decrease when harvesting a larger percentage of residues
In general the residue supply costs at farm gate are found to decrease when an increasing percentage of the residues is harvested. This is explained as follows. Crop and residue are harvested in one pass and a chosen percentage of the residues processed by the combine harvester is collected in this process. Thus, capacity of the machinery harvesting the residues is determined by the residue output from the combine. In other words, if in a certain field only a low percentage of the produced residues can be harvested due to sustainability requirements, the 'residue harvesting equipment' is running below their maximum capacity, increasing cost. Using equipment with a lower capacity is found not to be cost-effective; the higher costs were mainly due to the baler, but using a smaller baler increased bale hauling cost more than it reduced baling cost. A similar relation was found by (Graham et al. 2007, Brechbill, Tyner 2008).

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Appendices

1 Appendix A: Description and validation of the Rothamsted organic carbon model.

Model description
Figure 34 presents an overview of the soil carbon system as modelled. The organic material that is input to the system decomposes and partly ends up as soil organic matter which is divided between four active pools: Decomposable organic matter, Resilient organic matter, humified organic matter and microbial biomass. There is also a small amount of carbon present in the (inactive) inert organic matter pool. Each active carbon pool has a characteristic turnover rate based on the first order kinetics, depended on the temperature, availability of moisture and whether the soil is covered or fallow.

First of all, the organic inputs are divided into decomposable plant material and resilient plant material dependent on the nature of the material. For all agricultural residues a DPM/RPM ratio of 1.44 is used. Both the DPM and RPM decompose and the carbon is divided between the humus, microbial biomass and CO_2. Each carbon pool

The following sections discuss the partitioning of organic inputs between either microbial biomass and humus or CO_2 material and thereafter how the turnover rates are influenced by temperature, moisture availability and the presence or absence of a soil cover (in this case referring to the number of months that a crop is present on the soil.

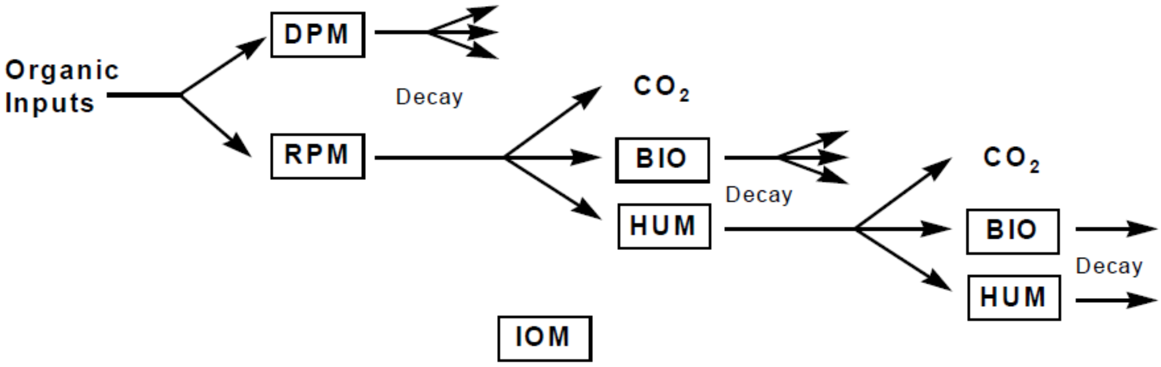

Figure 34: Overview of the carbon fluxes in the soil system as modeled by the Rothamsted carbon model. DPM: decomposable plant material, RPM: Resistant plant material, BIO: Microbial biomass, HUM: Humified organic matter, IOM: Inert organic matter. adapted from (Rothamsted carbon model).

1.1.1 Calculation of the turnover rates for the different pools.

The rate of decay is determined by the temperature, moisture availability and presence of a soil cover. Every compartment contains Y tonne C /ha then at the end of the month, X is reduced according to $Y * e^{-abckt}$ Equation **17**.

$$Y * e^{-abckt}$$

Equation 17: Formula for the calculation of the specific turnover rate of each carbon pool.
Where:
- *Y*: Amount of carbon present at the beginning of the month (tonne/ha)
- *a*: Rate modifying factor for temperature.
- *b*: Rate modifying factor for moisture.
- *c*: Rate modifying factor for soil cover.
- *k*: Decomposition rate constant for a specific compartment, see Table 82
- *t*: 1/12 since the k is the annual decomposition rate.

Soil organic carbon pool	k ($year^{-1}$)
Decomposable plant material	10,0
Resistant plant material	0,30
Microbial biomass	0,66
Humified organic matter	0,02

Table 82: Decomposition rate constant k ($year^{-1}$)

To illustrate the difference between the decay rate in the different carbon pools, the decay in each pool in one year starting at 50 tonne C/ha (without any C inputs during the year) is plotted in Figure 35 discarding the rate modifying factors a, b and c. The graph clearly shows that the C embodied in humified organic matter is of much greater value than C incorporated into decomposable plant material. Which variables determine how the C is determined between the different pools and how much is lost as C will be discussed in section 1.1.2 after the rate modifying factors for temperature, moisture, crop cover have been discussed in section 1.1.1.1, 1.1.1.2 and 1.1.1.3 respectively.

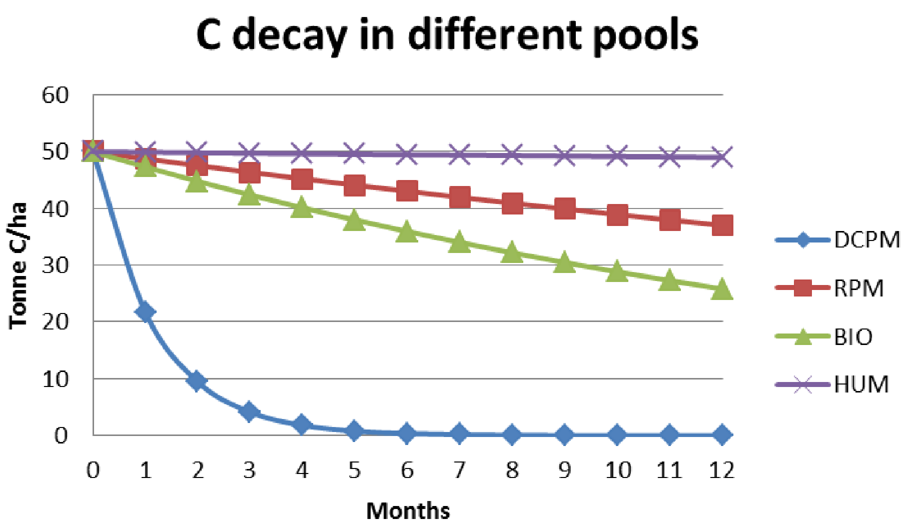

Figure 35: Monthly decay of organic carbon in the four different pools under standard conditions, i.e. not accounting for temperature, moisture, soil cover or clay content of the soil. The starting point of 50 tonnes C /ha was chosen arbitrarily.

1.1.1.1 Temperature effect (a)

The model uses the main monthly air temperature to estimate the soil temperature since these data are often readily available opposed to soil temperature data. The rate modifying factor a is described by Equation 18, the relation is depicted in Figure 11.

$$a = \frac{47.9}{1 + e^{\left(\frac{106}{T+18.3}\right)}}$$

Equation 18: Formula used to calculate the rate modifying factor for temperature.

Where:
- *a*: The rate modifying factor for temperature
- *T*: Monthly average air temperature in ºC.

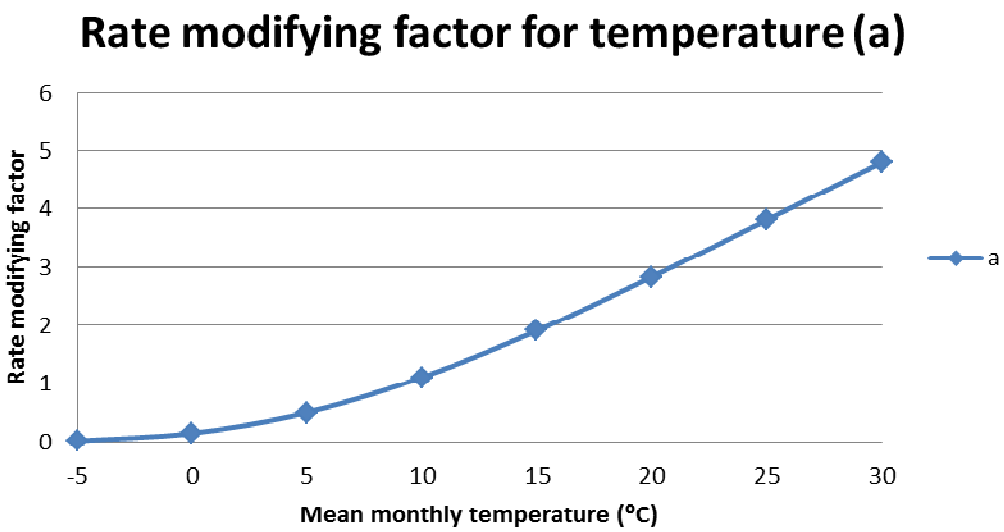

Figure 36: Rate modifying factor for temperature as a function of the monthly mean air temperature.

When the combining **Error! Reference source not found.** with Equation 17 it becomes clear that a higher temperature causes the decomposition of a certain carbon pool to be faster.

1.1.1.2 Moisture effect (b)

To calculate the amount of moisture present in the soil at a certain time monthly rainfall and potential evaporation data are required. The rate modifying factor is calculated based on the top soil moisture deficit (TSMD in mm). TSMD is dependent on the clay content, see Equation 19. The TSMD accumulates every month until a maximum is reached. Two different maxima are used dependent on whether the soil is covered by a crop or bare. The former is called the maximum top soil moisture deficit (maxTSMD) and the latter the maximum bare soil moisture deficit (maxBSMD) and they are calculated according to Equation 20 and Equation 21 respectively. The maxTSMD is higher than the maxBSMD since a lot of water is lost due to the respiration off the crops.

$$TSMD(mm) = Rainfall(mm) * potential\ evaporation(mm) * 0.75$$

Equation 19: Calculation of the top soil moisture deficit.

$$\max TSMD(mm) = -\left(20.0 + 1.3(\%clay) - 0.01([\%clay)]^2\right)$$

Equation 20: Calculation of the maximum accumulated top soil moisture deficit.

$$\max BSMD(mm) = \max \frac{TSMD(mm)}{1.8}$$

Equation 21: Calculation of the maximum accumulated bare soil moisture deficit from the maximum top soil moisture deficit.

Finally the rate modifying factor for moisture is calculated from equation 15

$$If\ accTSMD < 0.444 maxTSMD,$$

b=1.0

if not,

$$b = 0.2 + (1.0 - 0.2) * \frac{maxTSMD - accTSMD}{maxTSMD - 0.444 * maxTSMD}$$

Equation 22: Calculation of the rate modifying factor for moisture, b.

Since there the rate modifying factor for moisture is depend on two variables, the clay content of the soil and the TSMD, it cannot be plotted in one figure unless one of the two is assumed to be constant. To be able to illustrate this rate determining factor, the clay content will be assumed to be 20% in the following example, this means that the maxTSMD=-42mm (according to Equation 20). Figure 37 shows that a high top soil moisture deficit causes the decomposition to slow.

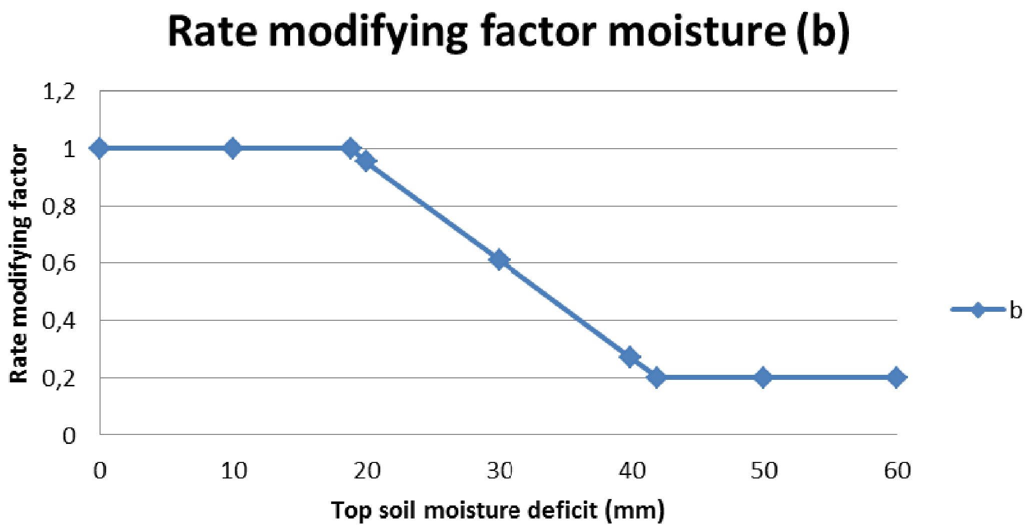

Figure 37: Rate modifying factor for moisture as a function of the top soil moisture deficit assuming a clay content of 20%.

1.1.1.3 Rate modifying factor for soil cover (c)

The presence of growing plants slows the decomposition of organic matter in the soil. Two different factors are used, c=0.6 if the soil is vegetated and c=1.0 if the soil is bare. It is important to note that soil cover in this case refers to presence of growing plants and not to residues.

1.1.2 Partitioning of the carbon that is lost as CO_2 and that remains

Each pool, except for the inert organic matter, in
Figure **34** decomposes. During this process, CO_2, Microbial biomass and humified biomass are created. The partitioning between the carbon lost as CO_2 and the carbon remaining as mirobial biomass or humified is determined from the clay content of the soil, the lower the clay percentage in the soil, the larger the fraction of carbon lost as CO_2. This relation is described by Equation 23.

$$x = 1.67(1.85 + 1.60\exp(-0.0786\,\%clay))$$

Equation 23: Formula for the calculation of the partitioning between CO_2 and BIO+HUM

Where x is the ration CO_2/(BIO+HUM)

The relation is depicted in Figure 38.

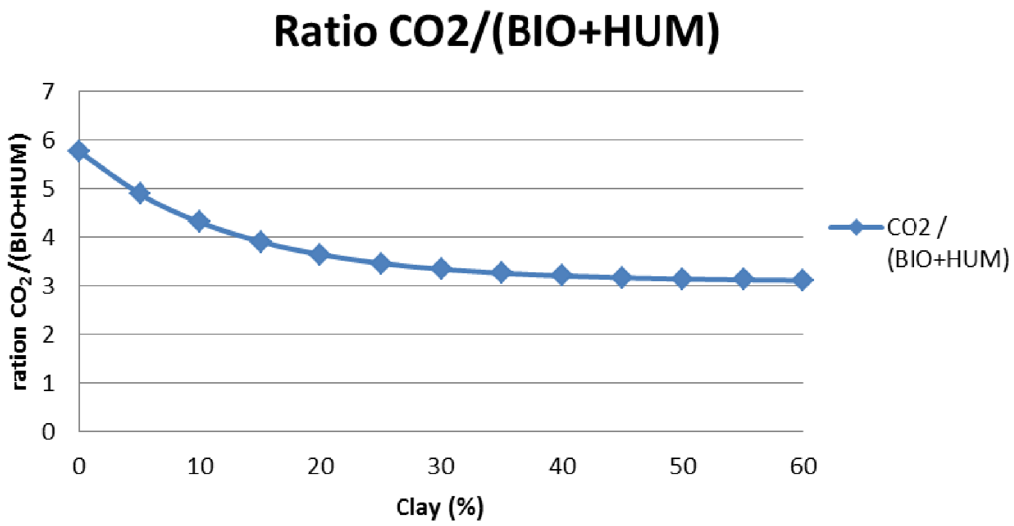

Figure 38: The effect of clay on the ration between the CO_2 released and the (BIO+HUM).

1.1.3 Model validation

The Rothamsted carbon model has been validated on multiple occasions using test trials worldwide. In a study by Coleman et al. (Coleman et al. 1997) the model was fitted to data from 18 different experimental treatments on six long-term experimental treatments in Germany, England , the USA, the Czech Republic and Australia. First the model was run provided the annual plant carbon input to predict the carbon content at the start of the experiments. Using the initial soil organic carbon content as a starting point the model was fitted to the different experimental treatments. The model gave an acceptable approximation to the measurements for 14 treatments but with 4 treatments the fit was less satisfactory.

In a study by Cerri et al. (Cerri et al. 2007) the model was successfully used to simulate the SOC changes as en effect of land use changes from forest to pasture in the Brazilian Amazone. Nieto et al. (Nieto et al. 2010) used the Rothamsted carbon model successfully to predict the SOC dynamics under different land uses and soil management systems in a Mediterranean olive grove.

These three studies show that the model can be successfully used to predict SOC changes for different land uses (or land use changes), under different management conditions, for different climatic conditions and for different soil types.