UNIVERSITY OF COPENHAGEN

Technical potentials of biomass for energy services from current agriculture and forestry in selected countries in Europe, The Americas and Asia

Bentsen, Niclas Scott; Felby, Claus

Publication date:
2010

Document version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Bentsen, N. S., & Felby, C. (2010). *Technical potentials of biomass for energy services from current agriculture and forestry in selected countries in Europe, The Americas and Asia*. Forest & Landscape, University of Copenhagen. Working Papers / Forest & Landscape, No. 55

FOREST & LANDSCAPE

Technical potentials of biomass for energy services from current agriculture and forestry in selected countries in Europe, The Americas and Asia

FOREST & LANDSCAPE WORKING PAPERS 55 / 2010

Niclas Scott Bentsen and Claus Felby

FACULTY OF LIFE SCIENCES
UNIVERSITY OF COPENHAGEN

Title
Technical potentials of biomass for energy services from current agriculture and forestry in selected countries in Europe, The Americas and Asia

Editors
Niclas Scott Bentsen and Claus Felby

Publisher
Forest & Landscape Denmark
University of Copenhagen
Rolighedsvej 23
DK-1958 Frederiksberg C
Tel. +45 3533 1500
Email sl@life.ku.dk

Series-title and no.
Forest & Landscape Working Papers no. 55-2010 published on www.SL.life.ku.dk

ISBN
978-87-7903-507-2

DTP
Karin Kristensen

Citation
Niclas Scott Bentsen and Claus Felby 2010: Technical potentials of biomass for energy services from current agriculture and forestry in selected countries in Europe, The Americas and Asia. Forest & Landscape Working Papers No. 54-2010, 31 pp. Forest & Landscape Denmark, Frederiksberg.

Summary

This report is a survey on the technical potential of biomass from current agriculture and forestry in the regions; Europe incl. Russia and Ukraine, USA, Canada, Brazil, Argentina, China and India. The report provides projections for agricultural residue production assuming availability of fertilizers, plant protection and mechanisation. Data for land use, crop yield and production, agricultural residues, forestry potential and surplus land are included in the survey.

This survey confirms a number of previous findings showing that there is a large potential of non-food biomass already present in agriculture and forestry. Furthermore the results also show that in some regions the yield from existing agriculture can be significantly increased by simply applying other agricultural practice and technology.

The technical biomass potential based on current global agriculture and forestry has a considerable potential for increased biomass production by simply just collecting a larger share of the biomass already produced. In practice this means that on basis of current land areas for agriculture and forestry it will be possible to establish and build a 2nd generation bioethanol industry. This can be done without conflicting with food production, just as there is a large potential for increased food production without increased agricultural area.
The potential from forestry is limited by current regulation e.g. US federal land is not included. The figures on the short term potential do therefore not represent the full biological potential of the forest.

The main results and key figures are:

- The total crop production from agriculture in all regions is 5.1 Gton.
- The total amount of non-food biomass produced from agriculture is 3.3 Gton
- There is an almost equal amount of agricultural residues of approximately 0.6 to 0.7G ton from each of the regions Europe, USA, India and China.
- Europe outside EU27 and the United States of America has a potential of increasing forest production significantly without harvesting more than the current increment.

The figures given here represent the full amount i.e. 100% of the biomass in the field or forest that may be collected. In real life the full amount will not be collected due to technical, economical and environmental reasons. Realizing the technical potential does not come by itself. A major concern is that by removing a larger share of the biomass, a more careful agricultural practice will be needed in order not to deplete the soil of carbon. This will require not only improved agricultural technology but also a new set of agricultural policies providing the necessary economical and environmental incentives for a sustainable biomass supply. For business scenarios realistic and sustainable estimates can be made assuming 50% of agricultural residue recovery.

Content

1. Introduction

This report is a survey of the technical potential for biomass supply from current agriculture and forestry. The potential is based on current production of crops and trees as well as current areas of forestry and agriculture. The figures included represent the technical potential, meaning the actual biomass produced, which is not necessarily the amount of biomass that can be collected from an economical and ecological perspective. A further description of different biomass potentials is given in the report.

The biomass potential is estimated for:
- Geographical Europe
- USA
- Canada
- Brazil
- Argentina
- China
- India

Africa, Australia, New Zeeland, Siberia and a number of Asian countries are not included. The reason why these areas and countries have been omitted is that they are either to geographically remote, are already exploited with a low short term potential for increased production, have very sensitive ecosystems, insufficient agricultural production or that they lack a sufficient infrastructure for increased biomass supply.

The data collected and analysed are land areas for crops and forests, crop yields, forest growth and the resulting energy output for combustion or 2nd generation bioethanol. In the written part of the survey not all data is presented, only the main findings. Detailed data and figures can be found in the accompanying excel spreadsheet.

The data in the survey has been collected primarily from official and recognised statistics databases. The data sources represent the best and most reliable available data on land use, agriculture and forestry, but as with most other statistics on natural resources they should be approached with the knowledge that they are not complete and may contain errors. Nevertheless the data are in most cases reliable and well documented.

In the case of wood production and incremental forest growth, statistical data has not been available from all regions/countries. Furthermore the potential from forestry is limited by current regulation e.g. US federal land is not included. The short term potential does therefore not represent the full biological potential from forests.

Surplus land and pasture is included in the listing on land use. Estimation of the potential biomass production from these areas will inevitably have a large variation, and the figures included in this report must be used with caution. A conservative approach of low intensity biomass production from these areas should be applied, in order to avoid conflict with potential negative environmental impact.

The potential use of surplus land and pasture is often highlighted as having a very large potential. This report shows that there is an immediate and probably easier accessible biomass potential from existing agriculture and forestry that can be realised. The potential biomass supply from existing agriculture and forestry appears more than adequate to supply the build up of a new biobased industry for production of fuels and chemicals.

The report is composed of a short introduction to plant growth followed by an overall presentation of the biomass potential divided into regions/countries. The final part of the report presents a description of terminology, methods and statistics used. Detailed data for individual countries and regions or provinces can be found in the excel spreadsheet.

1.1 The big picture

The results in this survey are grouped on three levels; total for all regions, regional and national figures. For each level the data provides figures on the area distribution of individual crops and forest types.
When analyzing and communicating the results, care should be taken that the data is relevant for the scenario in question. There are large differences with regard to biomass availability both on a regional and national level.

This survey confirms a number of previous findings showing that there is a large potential of non-food biomass already present in agriculture and forestry. Furthermore the results also show that in some of the regions; the yield from existing agriculture can be significantly increased by simply applying better agricultural practice and technology.

The main findings and key figures are:

- The total crop production from agriculture in all regions is 5.1 Gton.
- The total amount of non-food biomass produced from agriculture is 3.3 Gton.
- There is an almost equal amount of agricultural residues of approximately 0.6 to 0.7 Gton from each of the regions Europe, USA, India and China.
- Europe outside EU27 and the United States of America has a potential of increasing forest production significantly without harvesting more than the current increment.
- There is a large potential for increasing the production of both crops and residues in most regions/countries.
- An additional biomass potential can be realized from pastures or surplus, but current data is not reliable to give anything but loose estimates.

The following figures present a summary of the main results of this analysis. Results are presented for countries/regions with large biomass potential; EU27, geographical Europe minus EU27, United States of America, Canada, Brazil, Argentina, China and India.

The technical potential of agricultural residues from the eight selected crops sums up to almost 3.3 Gton (fresh weight) pr year, with the United States of America and China providing the biggest potentials (fig. 1).The global potential of residues from these eight crops is almost 5 Gton pr year.

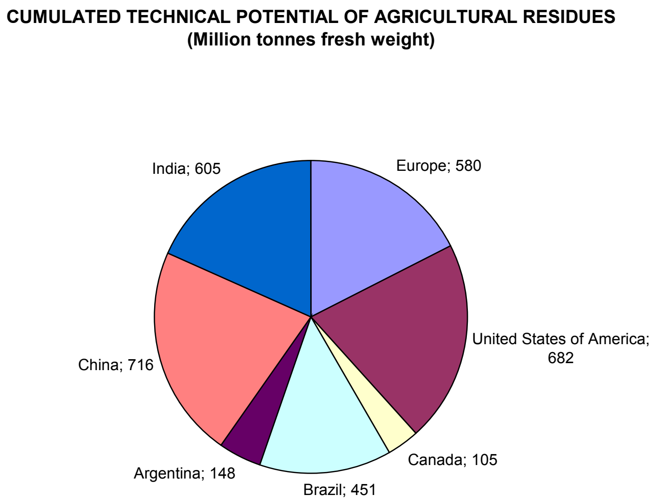

Figure 1. Technical potential of agricultural residues in selected countries.

Agricultural crops included in the report cover the major crops of the world. A summary of crop residue potentials from geographical Europe, United States of America, Canada, Brazil, Argentina, China and India (fig. 2) show that wheat and maize each has a residue potential of more than 600 Mton (fresh weight). Rice, soy bean and sugar cane residue potentials are each between 350 and 450 Mton. Barley, rape seed and sugar beet potentials lie between 100 and 150 Mton.

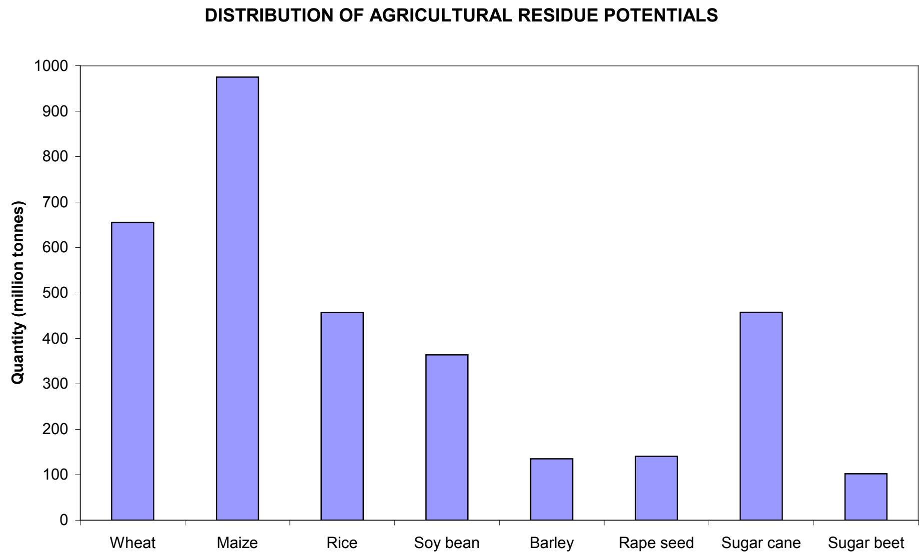

Figure 2. Distribution of technical potential of residues between agricultural crops. Values represent summed quantities for Europe, United States of America, Canada, Brazil, Argentina, India and China

With current conversion technologies the amount of cellulose available is of certain interest for the production of ethanol. The countries/regions in focus have an annual cellulose potential from agricultural residues of 994 Mton, and further 618 Mton of hemicellulose and 457 Mton of lignin.

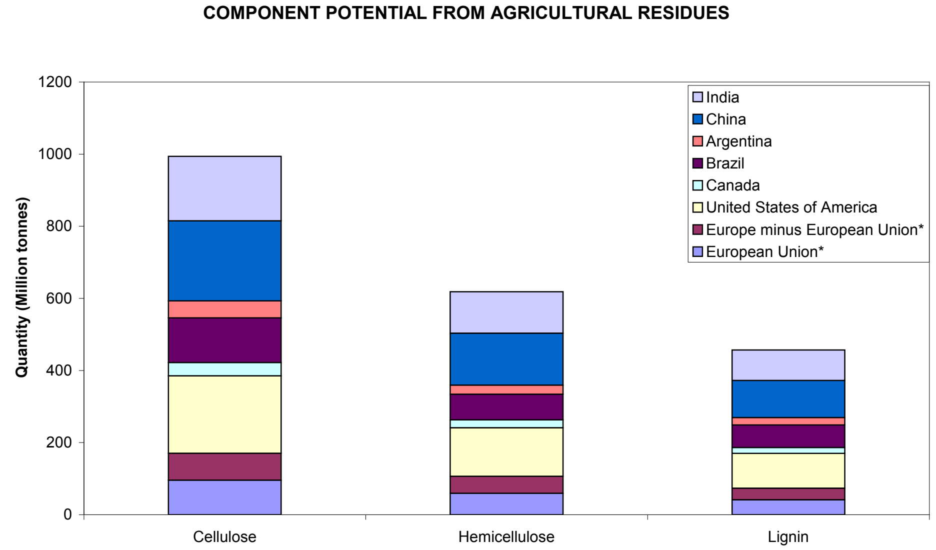

Figure 3. Technical potential of cellulose, hemicellulose and lignin from agricultural residues.

Forests and forestry are also a major potential source of cellulose. The current production of industrial round wood and wood fuel in the five countries/regions corresponds to 425 Mton, with Europe being the biggest supplier.

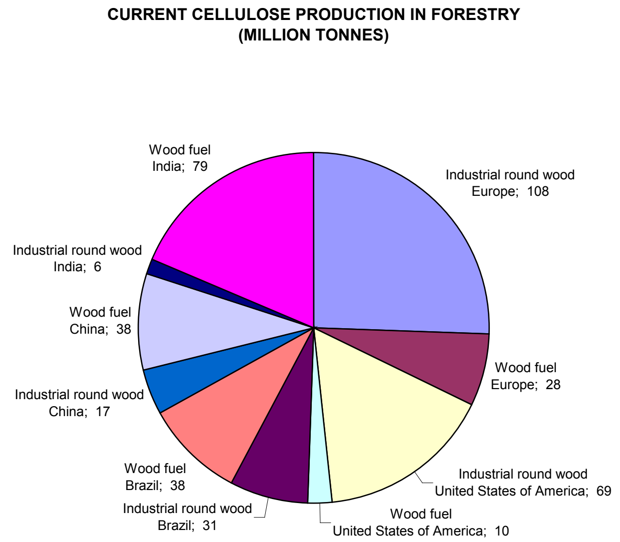

Figure 4. Current harvest of cellulose from forests

Chemical energy bound in biomass materials (expressed as higher heating value, HHV) comprising crop residues and forest production is for United States of America 14.6 EJ, for China 14.8 EJ, for Europe 15.7 EJ, for India 15.8 EJ and Brazil 11 EJ. Comparisons with other assessments (table 4) are not easy as they differ in methodology and temporal scope.

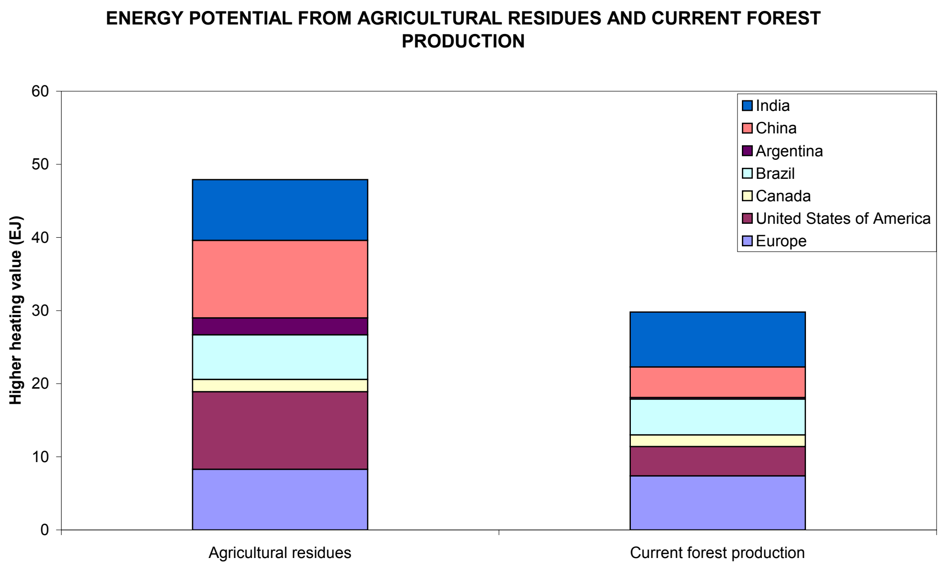

Figure 5. Higher heating value (HHV) of agricultural residue potentials and current forest production.

1.2 Limits to plant growth

How much biomass can we actually produce from agriculture and forestry? When estimating and evaluating the potential supply of a given plant biomass from crops and trees, the question on what is the real upper limit for how much biomass we can produce from a given area often arise. How much biomass could we harvest regardless if it is grown in the sea or on land, and which factors may limit the growth?

As with other living organisms the growth of plants is dependent upon their own metabolism and the rate by which they can feed their organism with energy and nutrients. In practice this means that the levels of water, CO_2, nutrients and light combined with the physiology and biochemical pathways, will limit the efficiency by which plants convert solar energy to biomass. On top of this there are the socioeconomic factors regulating the intensity and efficiency by which humans can explore plant biomass production.

The upper limit for biomass production is the photosynthesis by which plants convert light to biomass. Plants have developed two different pathways for photosynthesis known as C3 and C4 photosynthesis based on the first reaction product of the Calvin cycle. In general C4 photosynthesis is more efficient just as C4 plants are better suited for dry climates, but it will not perform well in colder climates.

Only 43% of the incoming light can be adsorbed by the photosynthetic pigments in the plants, and the biosynthesis of carbohydrates, proteins, lignin and fats from photons, CO_2 and H_2O impose a further loss in the captured solar energy.

Taking all these factors into consideration, the maximum efficiency for C3 and C4 photosynthesis is 4.6 % and 6.0 % respectively (Zhu et al., 2010). These levels are generic and are thus the maximum possible production regardless if we are looking at cereals, tress, herbs, algae etc. The resulting biomass production/ha as a function of the available light is shown in table 1. The numbers are indeed impressive compared to the realised yields from crops and trees which typically are a factor of 10-20 lower.

Location	Annual solar radiation	PAR	C3 plant biomass maximum	C3 realised yield	C4 plant biomass maximum	C4 realised yield
	GJ ha^{-1}	GJ ha^{-1}	T ha^{-1}	T ha^{-1}	T ha^{-1}	T ha^{-1}
Denmark	36000	15500	87	2-20	114	2-25
Southern Europe	54000	23200	130	2-45	171	2-60
Equator	72000	31000	174	2-60	227	2-120

Table 1. Maximum theoretical and realized biomass production on 1 ha. Theoretical figures are calculated from the solar radiation and the levels of photosynthetic active radiation (PAR) assuming 100% efficiency of photosynthesis and plant metabolism. The energy content of biomass is assumed 19 MJ kg^{-1}.

1.3 Current yields

The theoretical yields of several hundreds of tons/ha are far from what is realised in agriculture and forestry. An example is the average yield of wheat in e.g. Russia, which including straw, kernels, leaves and roots is 4.5-5 t/ha, but record yields of more than 25 tons of biomass/ha has been reported. However, other crops and trees such as sugarcane and eucalyptus may produce more than 100 t/ha and 50 t/ha respectively, and a large variation and thus potential exists.

The major limiting factor for biomass production from land-based plants is the amount of water available, and even for irrigated and optimally rain fed crops there will still be water limitations. This is caused by factors such as; water loss through the stomata cells by which the plants take up CO_2, the uptake and transport capacity of the root system and the moisture transport through the soil. Thus the physiology and structure of the water transport and usage in the plant and soil restricts the potential growth of the plants. For plants in temperate and subtropical areas also the lower temperatures will reduce the growth rate and further limit the productivity.

Another major limitation is the availability of nitrogen. This can be overcome by adding excess fertilizer, but also here there are limitations in the rate and efficiency by which the root system can adsorb and transport the nitrogen.

CO_2 limitation is often highlighted as one of the factors reducing the potential plant growth. In reality this factor is overestimated and water and nutrient limitations are the main limiting factors. The evolution of plants has adapted them to a low level of CO_2, and at CO_2 levels above 400 ppm the effect of increased CO_2 is diminishing.

1.4 What are realistic yields?

Achieving record yields such as 25 t biomass/ha of e.g. wheat, may be practically possible but not economic realistic, as the required input of water and nutrients will be too costly. For a number of crops the average yields are substantially below what can be obtained through good agricultural practice using currently available technology. A good example is wheat where e.g. the average cereal yield in Russia of 1.9 t/ha is substantially below the 5-7 tons/ha which can be obtained for rain fed wheat using good agricultural practice and current technology. Increased use of fertilizer and access to farming equipment especially in Eastern Europe, Ukraine and European Russia would add several hundred millions of tonnes to the wheat production.

On top of these limitations there is the human component; the farmer. For practical and economical reasons the farmer can not comply with the ideal tending of a given crop, just as suboptimal planting and seed quality can not be corrected during the growing season.

A list of the most relevant biophysical and socioeconomic factors determining biomass yield are provided in table 2. A rule of thumb is that practical experience shows that for a given area and agricultural production system 80% of the yield potential can be realised by the farmers.

Biophysical factors	Socioeconomic factors
Nutrient deficiencies and imbalances (nitrogen, phosphorous, potassium, zinc, magnesium etc.)	Profit maximization
Water stress	Risk aversion
Flooding	Inability to secure credit
Suboptimal planting and seed quality	Limited time devoted to activities
Soil problems (salinity, alkalinity, acidity, compaction etc.)	Lack of knowledge on agricultural practice
Weed pressure	Insufficient infrastructure for transport and storage
Insect damage	
Fungal and viral disease	
Lodging (from wind, rain and hail)	

Table 2. The major biophysical and socioeconomic factors limiting plant growth and harvest yield (Lobell et al., 2009).

Therefore when estimating biomass yields from agriculture and forestry one should always apply a conservative approach, and on top of every modelling consider the biological, physical and socioeconomic factors limiting the biomass production.

However, the technical biomass potential based on current global agriculture and forestry has a considerable potential for increased biomass production by simply just collecting a larger share of the biomass already produced.

Realizing the full technical potential does not come by itself. A major concern is that by removing a larger share of the biomass it will require a more careful agricultural practice in order not to deplete the soil of carbon. This will require development of agricultural technology as well as a new set of agricultural policies providing the necessary economical and environmental incentives for a sustainable biomass supply.

1.5 On resource potentials

Biomass resource potential is indeed an area where various estimates can be found. Individual studies reach different conclusions on the potential for bioenergy due to the use of different modelling approaches, assumptions, underlying data, and very important different definitions of the term potential. The potential can roughly be identified in four different ways: Theoretical, technical, economic or sustainable. However, neither the definition nor the application of the terms is unambiguous.
Theoretical potential is limited by ultimate physical constraints as solar radiation and surface area. Estimates of theoretical potential usually build on methodology from the natural sciences.

Technical potential is not uniquely defined in literature but encompasses potentials limited by factors relating to current technology (land use, agricultural practices, and forestry practices) and plant physiology (photosynthetic efficiency, respiration loss, partitioning, water use efficiency and those derived hereof as crop yield and harvest index). The technical potential is what is achievable with current applied or best available technology and practices.

The economic potential is the subset of technical potential that can be utilised under current economic and political conditions. The economic potential is very dependent on assumptions on economic behaviour, price development and political climate (political incentives/restrictions and international trade agreements). Estimates build on theory from the social sciences.

Sustainable potential is a subset of either technical or economic potential and must take the three pillars of sustainability (environment, social and economic) into consideration. As no clear-cut definition or even a generally accepted interpretation of the term sustainability exists estimates of sustainable potential may vary substantially. Estimates on this category build on theory from natural, social and biological sciences.

As a general rule it can be expected that different potentials rank as:

Theoretical > Technical > Economic > Sustainable

1.6 Review of current literature

The potential of renewable resources has been subject to much research and debate over the last years for many reasons. International agreements on reducing green house gas emissions (e.g. Kyoto Protocol, EU RES Directive, EU 20:20:20 Plan) has put substantial pressure on politics promoting and sustaining the use of alternative energy carriers. The sky rocketing of oil prices in 2008 turned commercial attention towards alternative resources and at the same time food prices grew dramatically, which led to substantial concern over the use of food crops and agricultural lands for energy purposes. Table 3 lists recent estimates of bioenergy potentials with various geographical and temporal scopes.

Reference	Modelling type	Potential type	Area type	Geographical scope	Year	Potential (EJ)
(Campbell et al., 2008)	GEO	SUS	Abandoned agriculture (crops and pasture)	World		0.032 -0.041
(de Wit and Faaij, 2010)	TECH + ECON	ECON	Energy crops	EU27+Ukraine	2030	1.7-12.8
			Agriculture residues			3.1-3.9
			Forest residues			1.4-5.4
(Ericsson and Nilsson, 2006)	TECH	TECH/SUS	Forest residues	EU15	2015-25	0.44-0.88
				ACC10		0.15-0.29
			Forest industry residues	EU15		0.83
				ACC10		0.22
			Agricultural residues	EU15		0.47-0.67
				ACC10		0.15-0.26
				Ukraine		0.06-0.15
			Energy crops (10% of arable land)	EU15		1.15
				ACC10		0.39
			Energy crops (25% of arable land)	EU15		2.87-3.73
				ACC10		1.38-1.8
(Smeets et al., 2004)	GEO/TECH	TECH	Dedicated energy crops + agricultural and forest residues + surplus forest increment	North America	2050	27-195
				Latin America + Caribbean		58-252
				W. Europe		8-25
				E. Europe		4-29
				CIS + Baltic		48-235
				Near East + N. Africa		2-39
				Sub-Saharan Africa		46-350
				South Asia		22-38
				East Asia		15-188
				Oceania		40-115
			Forests	World		20-38
(Smeets et al., 2007)	GEO/TECH	TECH	Dedicated energy crops + agricultural and forest residues + surplus forest increment	North America	2050	39-204
				Latin America + Caribbean		89-281
				W. Europe		13-30
				E. Europe		5-29
				CIS + Baltic		83-269
				Middle East + N. Africa		2-39
				Sub-Saharan Africa		49-347
				South Asia		23-37
				East Asia		22-194
				Oceania		40-114
				Japan		2
(Schubert et al., 2009)	GEO/ECON	SUS	Agriculture + forest + waste	World	2050	80-170
(Hoogwijk et al., 2003)	TECH	TECH	Surplus agr. Land	World	2050	0-988
			Degraded land			8-110
			Agr. Residues			10-32
			For. Residues			10-16
(Doornbosch and Steenblik, 2008)	TECH	TECH	Total	North America		20.5
				South/Central America		84
				Europe + Russia		33.9
				Africa		69.7
				Asia		20.8
				Oceania		15.7
				World		244.6
(Dornburg et al., 2008)	TECH/ECON	ECON	Agr. + for. Residues + waste	World	2050	40-170
			Surplus for.			60-100
			Surplus agr.			120
			Degraded land			70
			Agr. Intensification			140
(European Environment Agency, 2007)	TECH/ECON	SUS	Agr. + for. + waste	EU-25	2010	7.95
					2030	12.35
(Fischer et al., 2010)	TECH/ECON	TECH	Agr. Residues	EU-15	2000-2002	1.427
				EU-12		0.569
				Ukraine		0.292
				EU-15	2030	1.206
				EU-12		0.331
				Ukraine		0.146
(Fischer and Schrattenholzer, 2001)	TECH/ECON	ECON		World	2050	350-450
(Hoogwijk et al., 2005)	GEO/ECON	GEO		World	2050	311-657
					2100	395-1115
		TECH			2050	234-493
					2100	297-838

Table 3. Overview of recent literature and estimates of the bioenergy potential under different assumptions, with different methodology and with different geographical and temporal scope. GEO = geographical; TECH = technical; ECON = economic; SUS = sustainable.

2. Results

2.1 Descriptive statistics

2.1.1 Current land use

The current (2007) allocation of land to agriculture and forestry on the highest aggregation level is shown in figure 6. Forest make up far more land than agriculture and especially Russia and Brazil have vast areas. Permanent meadows and pasture are dominant in Brazil, China the United States of America and Europe outside EU27. Detailed data can be found in appendix A.

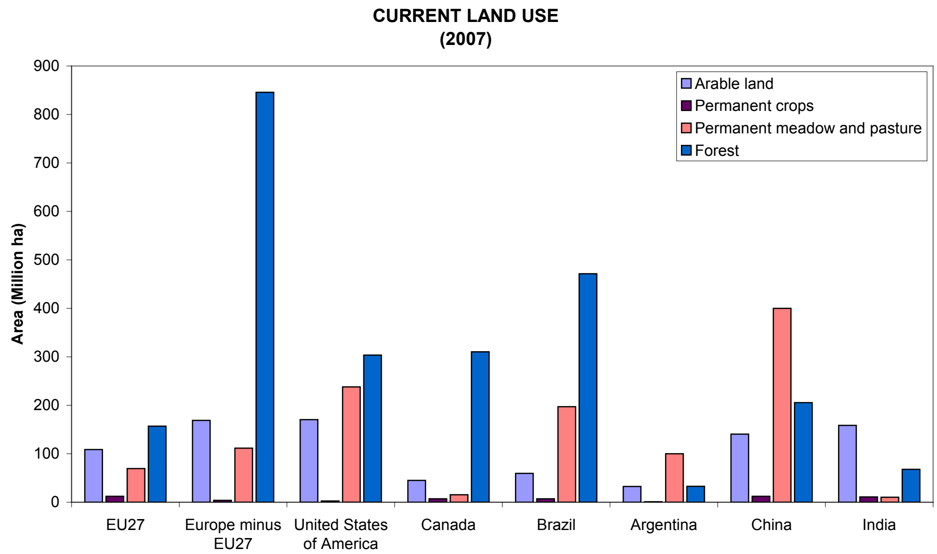

Figure 6. Land use in 2007based on (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2010a).

2.1.2 Current crop production

Current crop production on aggregated level of the world's main crop species (wheat, maize, rice, soy bean, barley, rape seed, sugar cane and sugar beet) is shown in figure 7. Detailed information on less aggregated levels can be found in appendix B.

Cereal production is dominant in EU27 and China. Maize heavily dominates agricultural production in the United States of America, but also in China significant production takes place. Soy been production takes place in the Americas. Rice production is mainly found in China and India, and sugar cane, being a tropical/sub-tropical crop grows mainly in Brazil and India.

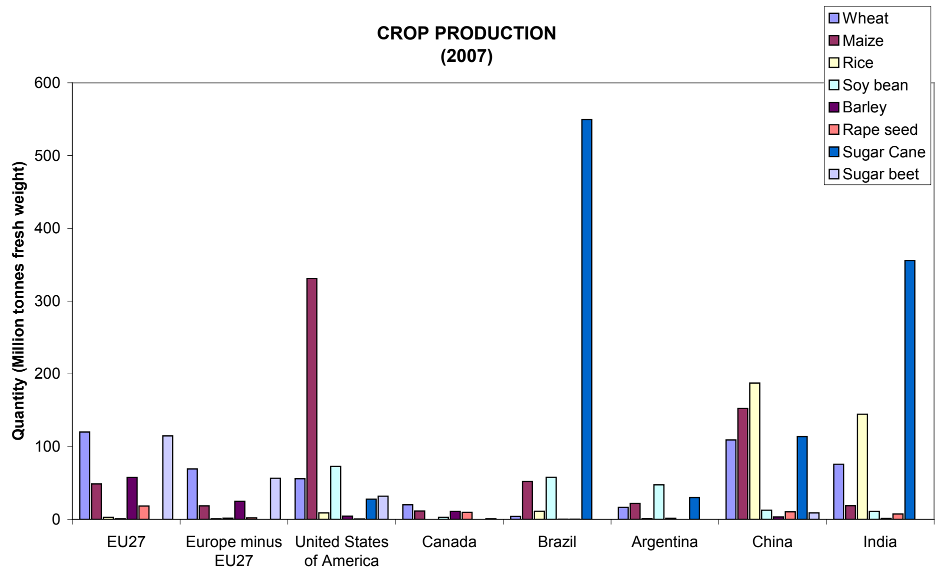

Figure 7. Agricultural crop production of selected crops in 2007based on (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2010a).

2.1.2 Current forest production

The production of industrial round wood and wood fuel on aggregated level based on coniferous and non-coniferous species is shown in figure 8. Industrial round wood is wood harvested for further processing in industries. Wood fuel is wood harvested with the purpose of combustion. Wood fuel usually consists of smaller dimensions, lower quality and harvest residues as compared to industrial round wood. Together these two product groups make up the entire forest production. A distinction between coniferous and non-coniferous species is made because of their structural differences. Coniferous species in general contain less hemicellulose and more lignin than non-coniferous species (see appendix D), which influences its convertibility especially through biochemical processes. Detailed information can be found in appendix C.

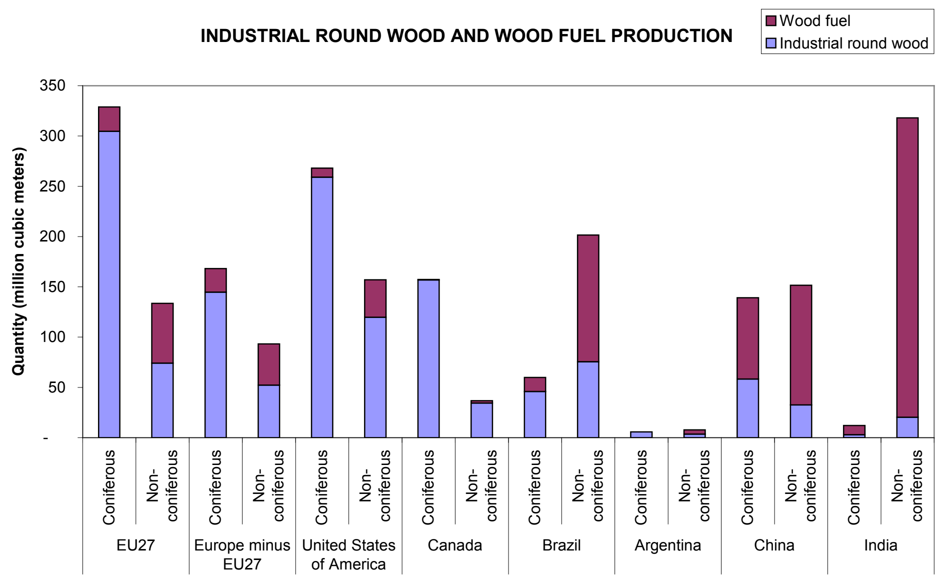

Figure 8. Forest production of wood fuel and industrial round wood of coniferous and non-coniferous species. Based on (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2010b).

2.2 Estimated resource potentials

The following section presents modelled data based on official data presented in section 2.1. The models are described in section 3.4. Technical potentials of agricultural residues on aggregated level are shown in figure 9. Data reflects the distribution of different crops in the world. Wheat is dominant in Europe and maize in the United States of America and China, sugar cane in Brazil and India and rice in China and India. Detailed data can be found in appendix F.

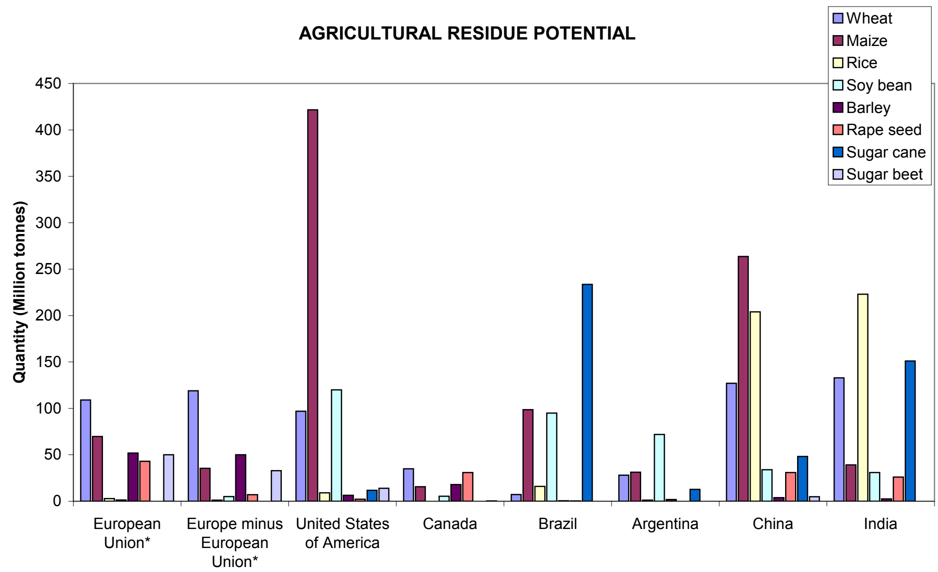

*Figure 9. Estimated technical potentials of agricultural residues in selected regions/countries. *European Union corresponds to EU27 minus Cyprus, Luxembourg and Malta.*

Biomass potentials from forestry for the countries from which forest increment is estimated are shown in figure 9 under the assumption that 50 % or 100 % of the increment is harvested. COP15 decided that green house gas emissions from further forest degradation should be avoided and preferably reversed (United Nations Framework Convention on Climate Change, 2009), why utilisation of 100 % of the forest increment is not desired. How big a proportion of the increment that can be utilised is not specified. Here we show the span between exploitation of 50 % or 100 % respectively. It can be seen from the negative values that most countries already now harvest more that 50 % of the increment in forests. Under the assumption that 100 % of the increment can be harvested it shows that the Russian Federation, USA and Canada has huge technical potentials of providing more biomass. For some European countries it is shown that even if 100 % of the increment is harvested their potential is negative (data not shown, see appendix I). This indicates that they already now harvest more than their increment, which obviously isn't sustainable. Caution must; however, be observed in interpreting these data as production and increment is estimated from different data sources and data on increment often is based on growth models rather than on actual measurements.

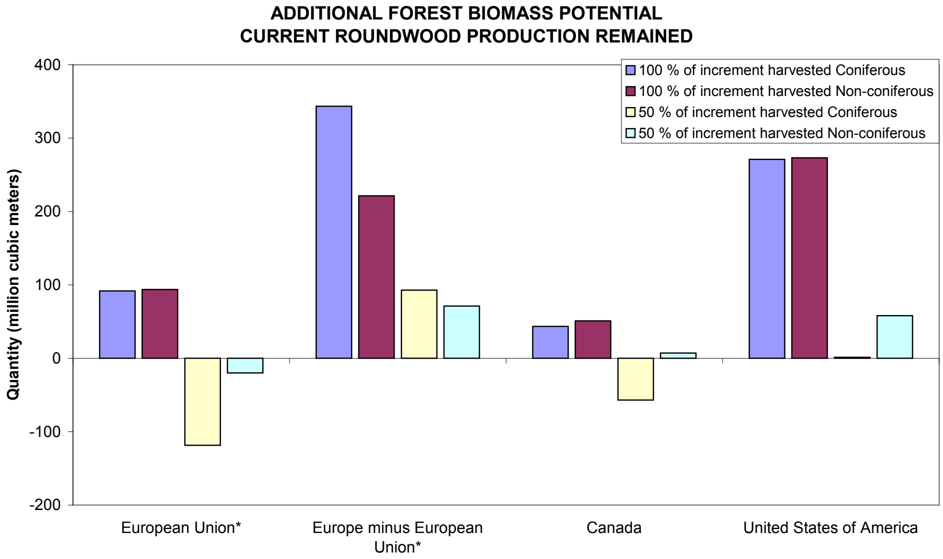

*Figure 10. Additional forest biomass potential from European Union, Europe minus European Union, Canada and the United States of America. *European Union corresponds to EU27 minus Cyprus, Luxembourg and Malta. Data on forest increment are not available for Brazil, Argentina, China and India.*

For the biotech industry estimates of the potential quantity of individual plant components is of certain interest. Figure 11 shows on aggregated level the potential of cellulose, hemicellulose and lignin respectively based on agricultural residues. The figure reveals that the composition of crop residues doesn't vary much except in Brazil where lignin tends to make up a slightly bigger proportion of plant components. Sugar cane being dominant in Brazil has relatively high lignin content. Appendix K provides detailed information.

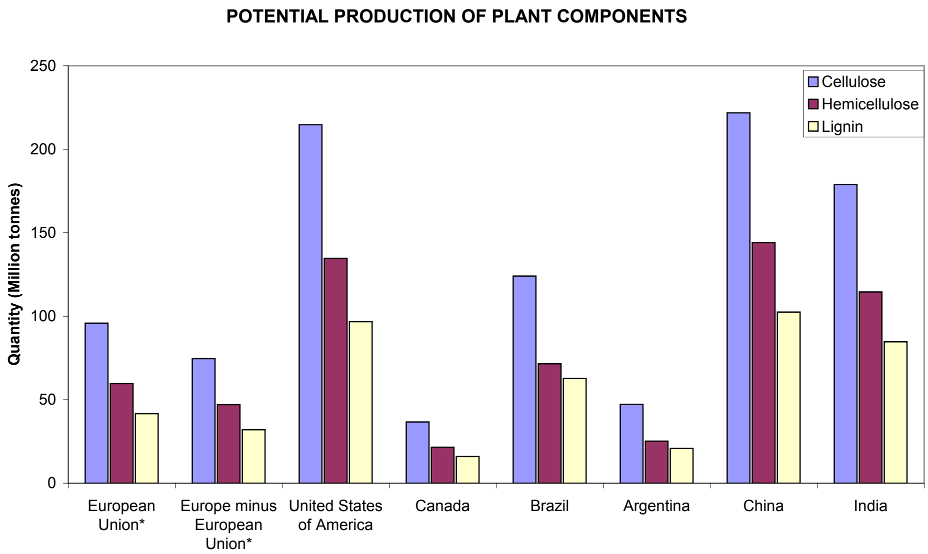

*Figure 11. Potential production of cellulose, hemicellulose and lignin from agricultural residues. *European Union corresponds to EU27 minus Cyprus, Luxembourg and Malta.*

The current production of plant components in forestry from either wood fuel or industrial round wood is shown in figure 12. Europe and the United States of America have a huge production of industrial wood. India has a huge production of wood fuel. Detailed information can be found in appendix L.

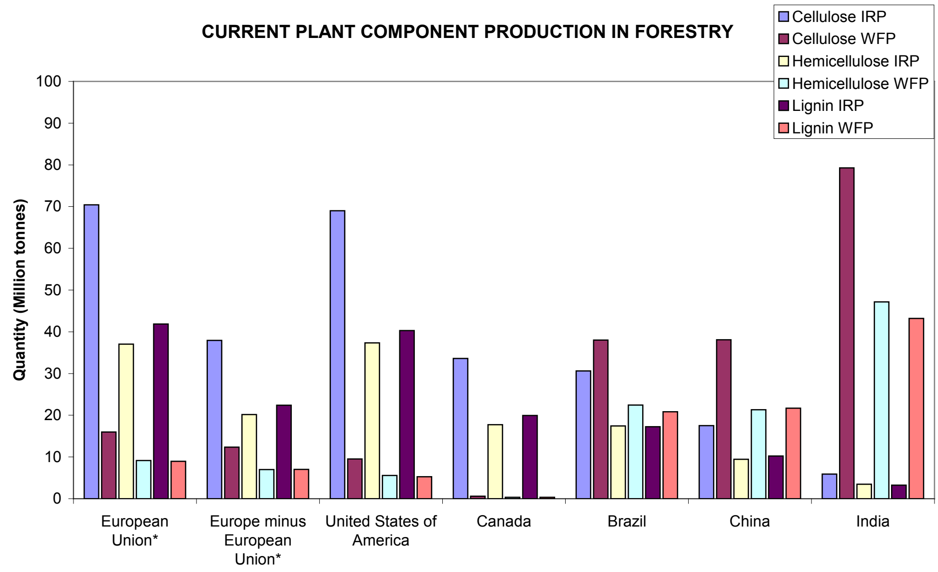

*Figure 12. Plant components in the current production of wood fuel and industrial round wood in selected countries. Argentina is excluded as their forest production is very limited. IRP = industrial round wood and WFP = wood fuel. *European Union corresponds to EU27 minus Cyprus, Luxembourg and Malta.*

Ethanol can be derived from cellulose and hemicellulose in either agricultural residues or forestry products. Due to the higher lignin content in wood, especially in wood from coniferous species it is not equally easy to extract the cellulose and hemicellulose from different types of residue. On the current technological level conversion of cereal straw to ethanol takes place on large demonstration /small commercial scale; whereas conversion of wood based products only take place on research and small demonstration scale. Figure 13 shows the potential of ethanol from agricultural residues, from the current wood fuel production and the estimated additional wood production under the assumption that current round wood production is maintained. Detailed information can be found in appendix M.

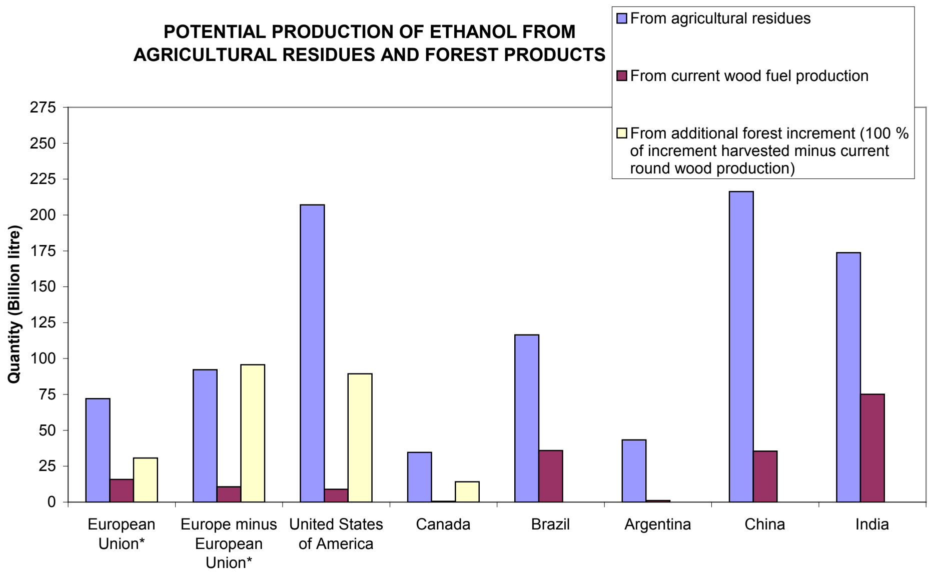

*Figure 13. Ethanol production potential from agricultural residues, wood fuel production and additional wood production. Conversion technology is assumed to convert cellulose and hemicellulose. Data on forest increment is not available for Brazil, Argentina, China and India. *European Union corresponds to EU27 minus Cyprus, Luxembourg and Malta.*

The current use of motor gasoline in the United States of America is 537 billion litre (in 2006) and correspondingly in EU27 144 billion litre (U.S. Energy Information Administration, 2010).

2.3 Agricultural intensification

Applying agro ecological zoning shows that crop yields can be increased substantially if countries have access to adequate technology, fertilisers, plant protection and improved cultivars. The potentials for increasing crop residue production vary between crops and regions (fig. 14). Especially for wheat straw there is a huge potential for increase in the European Union. Maize residue potentials can be increased in Brazil, China and India and rice in India. Combinations of crop and country/region that exhibit no or minor potential increase have been omitted from figure 14. The applied model shows no potential increase for sugar cane and sugar beet. This may be due to inadequacy of the model. These estimates must be approached with caution as they build on assumptions regarding residue potential under current crop yields and little is known when yields increase much above the current.

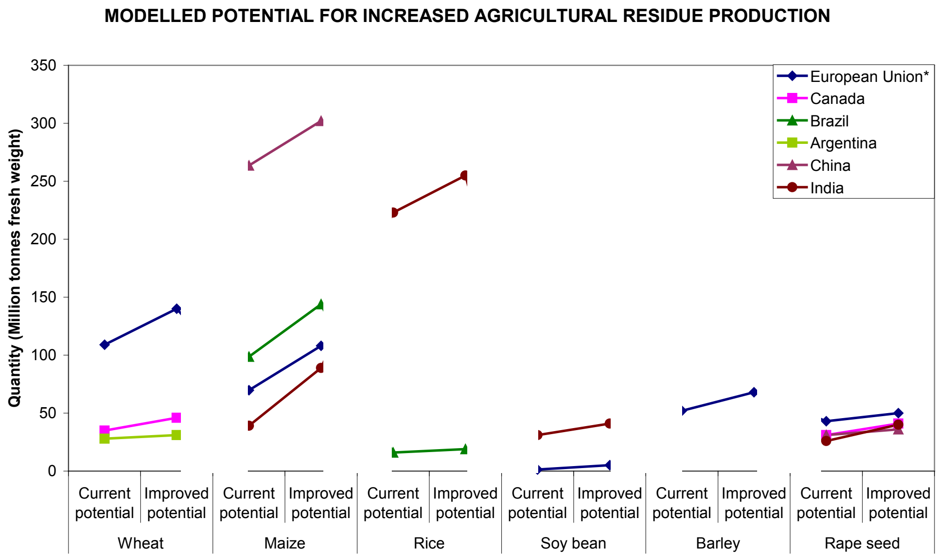

Figure 14. Modelled increase in agricultural residue production for selected crops and regions/countries. Estimates are based on the assumption that high input agriculture is practiced, which include fertilisation, plant protection, plant improvement, mechanisation, but not irrigation.
**European Union corresponds to EU27 minus Cyprus, Luxembourg and Malta.*

2.4 Surplus land

The amount of surplus agricultural land is estimated in various papers. (Smeets et al., 2007) find a surplus agricultural area in 2050 of 3.6 Gha, which potentially could be grown with woody bioenergy crops and yield 215 – 1272 EJ yr^{-1}. (Ericsson and Nilsson, 2006) find that willow grown on surplus agricultural land, which is land freed from agriculture and livestock production due to intensification, can produce 7.3 – 9.5 EJ yr^{-1} in EU15, 3.8 – 4.9 EJ yr^{-1} in the 10 states included in the European Union in 2004, 0.6 – 0.7 EJ yr^{-1} in Belarus and 3.7 – 4.8 EJ yr^{-1} in Ukraine.
(Campbell et al., 2008) find a global area of abandoned agricultural land of 385 to 472 Mha with the ability of producing 1.6 to 2.1 Gton of dry biomass. (Field et al., 2008) estimate an area of abandoned agricultural land of 386 Mha globally, however, with a substantial uncertainty of ± 50 %.

3. Methodology

3.1 Definitions and nomenclature

Definitions and abbreviations used in this report and the database are listed appendix 1.

3.2 Countries and resources included in the analysis

On the highest level of aggregation we include Europe, USA, Canada, Mexico, Argentina, Brazil, India and China. Providing a higher level of detail we include data for states/provinces of Europe (excluding Andorra, Channel Islands, Faroe Islands, Iceland, Isle of Man, Lichtenstein, Malta, San Marino, Gibraltar and Luxembourg due to size of resource potential), USA, Brazil and China. Regionalised agricultural data for India do exist but are not publicly available free of charge.

Agricultural crops included in this assessment are based on ranking crop production in the countries included and then include the most dominant crops based on production quantities. Crops included are wheat, maize, rice, soy bean, barley, rape seed/canola, sugar cane and sugar beet. Crop residues comprise straw for wheat, rice, soy bean, barley and rape seed; stover and cob for maize; bagasse and top+leaves for sugar cane; and top for sugar beet. Additionally forest resources are included, but at a higher level of aggregation due to data availability. Total forest production and increment is included as well as a division into coniferous and non-coniferous species groups.

3.3 Data sources

3.3.1 Agriculture

The assessment of agricultural production and residue potential builds on publicly available data. Aggregated data on land use, crop production and crop yield on national level is provided from (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2010a; FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2010b). Higher resolution data on land use, crop production and crop yield to the level of state/province is provided for USA by (United States Department of Agricultrue - National Agricultural Statistics Service, 2010), for Brazil by (Instituto Brasileiro de Geografia e Estatística, 2010), and for China by (National Bureau of Statistics of China, 2010). Note that the data on agricultural residues are indirect figures derived from the crop yields, see 2.5 for details. Very little direct data are available; however, reasonably accurate estimates can be made on the basis of crop yields.

3.3.2 Forestry

Data for forestry potentials are based on area and growing stock statistics from (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2006), estimates on forest increment from (UN-ECE/FAO, 2000) and production statistics (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2010b). Data are not directly comparable between the three data sources as are gathered with different methodologies.

3.3.3 Biomass conversion parameters

The conversion from primary biomass into energy carriers applicable in our current energy supply is based on data on composition of individual biomass fractions. The composition of agricultural residues can be estimated more accurately than the composition of forest products as they are more specific. The composition of sugar cane bagasse and maize stover is taken as average values from (U.S. Department of Energy, 2004). The composition of other resources in this analysis is based on average values from (ECN, 2010). An overview of conversion parameters used in this report can be found in appendix D.

3.3.4 Data quality

This assessment builds primarily on publicly available data compiled by governmental or intergovernmental bodies. While these bodies put a lot of effort into secure data quality, comprehensiveness and comparability it is evident that they derive from different sources and are collected using different methodologies.

Data on land use and agricultural production are derived from FAOSTAT. Forestry data are collected from three different sources from two different bodies. FAO provides data through their online database FAOSTAT and the Forest Resource Assessment 2005. United Nations Economic Commission for Europe provides data on forest increment in some countries. It must be noted that none of these sources are directly comparable, why forest resource potentials builds on adjustments to those data.

Agricultural residue production is modelled primarily from a recent and very comprehensive study on bioenergy potentials in Europe (Fischer et al., 2010). The model does; however seem to overestimate the potential of cereal residues from very high yielding countries. Data on agricultural residue production based on direct measurements is scarce. A model for wheat and barley residue potentials builds on the latest direct measurement of straw production in Denmark from 1994-1996 (Dansk Landbrugsrådgivning Landscentret, 2010) and a recent reference from India (Combustion Gasification & Propulsion Laboratory, 2009). The alternative model provides reasonable estimates for Denmark but have the drawback that it probably underestimates the residue potential for countries showing much higher cereal yields than Denmark.

3.4 Resource estimation

Below we estimate the technical potential of biomass and assume that 100 % of agricultural residues are technically available. This is not necessarily equal to an economic or sustainable potential. By convention, it seems, literature applies the assumption that 50 % of the residue production or of the unappropriated part can be harvested (Ericsson and Nilsson, 2006; Fischer et al., 2010). Removal of crop residues has an impact on the level of soil organic carbon, which is important for sustaining the productivity of soil. The actual limits of sustainable residue harvest is, however, dependent on micro geographical conditions as soil type, climate, farming practices and farming history and an assessment hereof is not within the scope of this paper.

The amount of agricultural residue is estimated as

$$ARP_{ij} = CP_{ij} \cdot RPR_j$$

with RPR as a stepwise linear function of crop yield (Y_j). RPR for low yielding cultivars is traditionally higher than that for higher yielding cultivars (Fischer et al., 2010). For maize, rice, soy bean, rape seed and sugar beet RPR is based on (Fischer et al., 2010). RPR functions based on (Fischer et al., 2010) seem to overestimate cereal residue production for very high yielding countries/regions. We adapt the functions used here to the range of yield data in appendix B such that the lowest estimate of the lower yield boundary is used as starting point of the function and the lowest estimate of the higher yield boundary is used as endpoint of the function. The function for rape seed is estimated with data from Denmark as high yield example (Statistics Denmark - statbank.dk, 2010) and from India as low yield example (Combustion Gasification & Propulsion Laboratory, 2009). RPR for sugar cane is assumed constant and based on (Koopmans and Koppejan, 1997). RPR functions are:

$$RPR_{wheat} = \left\{ \begin{array}{l} 1.75 \quad if \quad Y_{wheat} < 2708 \\ -0.000311 Y_{wheat} + 2.593395 \quad if \quad 2708 \le Y_{wheat} \le 6561 \\ 0.55 \quad if \quad Y_{wheat} > 6561 \end{array} \right\}$$

$$RPR_{maizestover} = \left\{ \begin{array}{l} 2.00 \quad if \quad Y_{maize} < 1500 \\ -0.000118 Y_{maize} + 2.065972 \quad if \quad 1500 \le Y_{maize} \le 9000 \\ 1.00 \quad if \quad Y_{maize} > 9000 \end{array} \right\}$$

$$RPR_{maizecob} = 0.273$$

$$RPR_{rice} = \left\{ \begin{array}{l} 2.00 \quad if \quad Y_{rice} < 2500 \\ -0.000146 Y_{rice} + 2.024140 \quad if \quad 2500 \le Y_{rice} \le 7000 \\ 1.00 \quad if \quad Y_{rice} > 7000 \end{array} \right\}$$

$$RPR_{soybean} = \left\{ \begin{array}{l} 3.50 \quad if \quad Y_{soybean} < 500 \\ -0.000734 Y_{soybean} + 3.703452 \quad if \quad 500 \le Y_{soybean} \le 3000 \\ 1.50 \quad if \quad Y_{soybean} > 3000 \end{array} \right\}$$

$$RPR_{barley} = \left\{ \begin{array}{l} 2.50 \quad if \quad Y_{barley} < 1000 \\ -0.000498 Y_{barley} + 2.997957 \quad if \quad 1000 \le Y_{barley} \le 4916 \\ 0.55 \quad if \quad Y_{barley} > 4916 \end{array} \right\}$$

$$RPR_{rapeseed} = \left\{ \begin{array}{l} 3.50 \quad if \quad Y_{rapeseed} < 1000 \\ -0.000600 Y_{rapeseed} + 4.100000 \quad if \quad 1000 \le Y_{rapeseed} \le 3500 \\ 2.00 \quad if \quad Y_{rapeseed} > 3500 \end{array} \right\}$$

$$RPR_{sugarcanetop+leaves} = 0.125$$

$$RPR_{sugarcanebagasse} = 0.3$$

$$RPR_{sugarbeet} = \left\{ \begin{array}{l} 0.70 \quad if \quad Y_{sugarbeet} < 10000 \\ -0.000005 Y_{sugarbeet} + 0.746154 \quad if \quad 10000 \le Y_{sugarbeet} \le 75000 \\ 0.40 \quad if \quad Y_{sugarbeet} > 75000 \end{array} \right\}$$

The potential for increasing residue potentials through agricultural intensification is evaluated by comparing actual yields with potential yields. Potential yields are estimated through agro ecological zoning, which estimates crop yields as limited by biophysical (solar radiation, soil type, temperature, precipitation evapotranspiration etc.) and agronomic (nutrient application, plant protection, mechanisation etc.) constraints (Fischer et al., 2002).

$$ARP\left(potential\right)_{ij} = \begin{cases} CP_{ij} \cdot RPR_j \quad if \quad Y\left(actual\right)_{ij} > Y\left(potential\right)_{ij} \quad and \quad A(actual)_{ij} < A(potential)_{ij} \\ A_{ij} \cdot Y\left(potential\right)_{ij} \cdot RPR_j \quad if \quad Y\left(actual\right)_{ij} < Y\left(potential\right)_{ij} \end{cases}$$

Forest resource potentials build on estimates of forest area available for wood supply (FAWS) and increment of the two species groups, coniferous and non-coniferous within FAWS. (UN-ECE/FAO, 2000) provides estimates of the proportion of the total forest area that is available for wood supply. These proportions with reference to the period 1990-1995 are assumed valid for the reference year for this analysis, 2007. Thus the current forest area available for wood supply is estimated by

$$\frac{FAWS2000_i}{total \quad forest \quad area\left(TBFRA\right)_i} \cdot forest \quad area\left(FAOSTAT \quad 2007\right)_i = FAWS2007_i$$

Estimation of current increment of coniferous and non-coniferous forests available for wood supply builds on data on forest composition as coniferous, broadleaved or mixed (UN-ECE/FAO, 2000) assuming that the current forest area has the same composition and in the reference period 1990-1995 and that the increment within the species groups is similar. This is an approximation as no accurate data on the current forest composition and increment exists.

Two models are used to estimate forest resource potentials. One model builds on the current production of wood fuel (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 2010b) and can be extracted directly from the table in appendix C. Second model builds on the assumption that respectively P = 50, 80 or 100 % of the forest increment may be harvested while the current production of respectively round wood or industrial round wood remains constant.

$$PFP_j = \sum \begin{cases} PI_j - IRP_j \middle| I_j \quad is \quad known \\ WFP_j \middle| I_j \quad is \quad unknown \end{cases}$$

Potential production of individual components, cellulose, hemicellulose and lignin from agricultural residues is estimated by:

$$CPO_{ik} = C_{jk} \sum_i ARP_{ij} \cdot \left(1 - MC_j\right)$$

Potential production of components from forestry is estimated by:

$$CPO_{ik} = RP_i \cdot (1 - VC)_{ij} \cdot r_{0j} \cdot C_j$$

Within species groups (conifers and non-conifers) wood densities can be expected to vary between geographical regions. Forest production statistics do not yield data on specific species level. We estimate an average density (r_0) of wood from different geographical regions as an average of abundant commercial species within species groups (Thomassen, 1991). We allocate individual countries to North America (Canada and USA), Central/South America (Mexico, Argentina and Brazil), Boreal Europe (Norway, Sweden, Finland, Estonia, Latvia, Lithuania and the Russian Federation) Temperate Europe (European countries not in the group above), China and India. Appendix D provides data on resource composition and regional wood densities.

Potential biomass production on fallowed, set-aside or idle land as well as potentials that can be realised through an intensification of livestock grazing in various parts of the world is dealt with qualitatively based on literature.

References

Campbell J.E., Lobell D.B., Genova R.C., Field C.B. (2008)
The Global Potential of Bioenergy on Abandoned Agriculture Lands. Environmental Science & Technology 42:5791-5794. DOI: 10.1021/es800052w.

Cengel Y.A., Turner R.H., Cimbala J.M. (2008)
Fundamentals of thermal-fluid sciences McGraw-Hill Higher Education, New York, USA.

Combustion Gasification & Propulsion Laboratory. (2009)
Crop residue details, Bangalore.

Dansk Landbrugsrådgivning Landscentret. (2010)
Farmtal Online, Dansk Landbrugsrådgivning.

de Wit M., Faaij A. (2010)
European biomass resource potential and costs. Biomass and Bioenergy 34:188-202.

Doornbosch R., Steenblik R. (2008)
Biofuels: Is the cure worse than the disease?, Revista Virtual REDESMA.

Dornburg V., Faaij A., Verweij P., Langeveld H., Ven v.d.G.W.J., Wester P., Keulen v.H., Diepen v.K., Meeusen M.J.G., Banse M.A.H., Ros J., Vuuren v.D., Born v.d.G.J., Oorschot v.M., Smout F., Vliet v.J., Aiking H., Londo M., Mozaffarian H., Smekens H. (2008)
Assessment of global biomass potentials and their links to food, water, biodiversity, energy demand and economy.

ECN. (2010)
PHYLLIS - The composition of biomass and waste, Energy Research Centre of the Netherlands

Ericsson K., Nilsson L.J. (2006)
Assessment of the potential biomass supply in Europe using a resource-focused approach. Biomass and Bioenergy 30:1-15.

European Environment Agency. (2007)
How much bioenergy can Europe produce without harming the environment?, EEA Report, Copenhagen.

Field C.B., Campbell J.E., Lobell D.B. (2008)
Biomass energy: the scale of the potential resource. Trends in Ecology & Evolution 23:65-72.

Fischer G., Schrattenholzer L. (2001)
Global bioenergy potentials through 2050. Biomass and Bioenergy 20:151-159.

Fischer G., Velthuizen H.v., Shah M., Nachtergaele F. (2002)
Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Fischer G., Prieler S., van Velthuizen H., Berndes G., Faaij A., Londo M., de Wit M. (2010)
Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios. Biomass and Bioenergy 34:173-187.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS. (2006)
Global Forest Resources Assessment 2005, FAO Forestry Paper, Rome. pp. 350.
FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS. (2010a)
FAOSTAT-Agriculture, Food and Agriculture Organizasion of the United Nations.
FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS. (2010b)
FAOSTAT-Forestry, Food and Agriculture Organizasion of the United Nations.
Hoogwijk M., Faaij A., Eickhout B., de Vries B., Turkenburg W. (2005)
Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. Biomass and Bioenergy 29:225-257.
Hoogwijk M., Faaij A., van den Broek R., Berndes G., Gielen D., Turkenburg W. (2003)
Exploration of the ranges of the global potential of biomass for energy. Biomass and Bioenergy 25:119-133.
IEA. (2007)
World Energy Outlook 2007. pp. 600.
Instituto Brasileiro de Geografia e Estatística. (2010) Levantamento Sistemático da Produção Agrícola, Instituto Brasileiro de Geografia e Estatística.
Koopmans A., Koppejan J. (1997)
Agricultural and Forest Residues - Generation, Utilization and Availability, Regional Consultation on Modern Applications of Biomass Energy, 6-10 January 1997, Kuala Lumpur, Malaysia.
Lobell D.B., Cassman K.G., Field C.B. (2009)
Crop Yield Gaps: Their Importance, Magnitudes, and Causes. Annual Review of Environment and Resources 34:179-204. DOI: doi:10.1146/annurev.environ.041008.093740.
Murphey W.J. (1993)
Tables for Weights and Measurement: Crops University of Missouri,Department of Agronomy.
National Bureau of Statistics of China. (2010)
China Statistical yearbook 2009, National Bureau of Statistics of China.
Schubert R., Schellnhuber H.J., Buchmann N., Epiney A., Grieshammer R., Kulessa M., Messner D., Rahmstorf S., Schmid J. (2009)
Future Bioenergy and Sustainable Land Use, WBGU, London.
Smeets E., Faaij A., Lewandowski I. (2004)
A quickscan of global bio-energy potentials to 2050
An analysis of the regional availability of biomass resources for export in relation to the underlying factors, Copernicus Institute - Department of Science, Technology and Society, Utrecht.
Smeets E.M.W., Faaij A.P.C., Lewandowski I.M., Turkenburg W.C. (2007)
A bottom-up assessment and review of global bio-energy potentials to 2050. Progress in Energy and Combustion Science 33:56-106.

Statistics Denmark - statbank.dk. (2010)
HALM1: Straw yield and use by region, crop, unit and use, Statistics Denmark.
Thomassen T. (1991)
Træ of Træmaterialer [Wood and Wood materials] Dansk Teknologisk Institut, Copenhagen.
U.S. Department of Energy. (2004)
Biomass Feedstock Composition and Property Database, U.S. Department of Energy,.
U.S. Energy Information Administration. (2010)
International Energy Statistics.
UN-ECE/FAO. (2000)
Forest Resources of Europe, CIS, North America, Austraila, Japan and New Zealand, Geneva Timber and Forest Study Papers, United Nations Economic Commission for Europe / Food and Agriculture Organisation of the United Nations, Geneva.
United Nations Framework Convention on Climate Change. (2009)
Copenhagen Accord, United Nations Office at Geneva, Geneva.
United States Department of Agricultrue - National Agricultural Statistics Service. (2010)
Census of Agriculture 2007, United States Department of Agricultrue.
Zhu X.-G., Long S.P., Ort D.R. (2010)
Improving Photosynthetic Efficiency for Greater Yield. Annual Review of Plant Biology 61:235-261. DOI: doi:10.1146/annurev-arplant-042809-112206.

Appendix 1

Abbreviations and definitions

FAO land use definitions

Agricultural area = Arable land + Permanent crops + Permanent meadows and pastures

Arable land = Temporary crops + Temporary meadows and pastures + Fallow land

Some discrepancies between FAO and national statistics in the amounts of land allocated to specific purposes are found. We assume the following relations between FAO and national statistics.

Relating to USDA NASS statistics:

Cropland ~ Temporary crops

Idle land ~ Fallow land

Pasture land - The level of discrepancy suggest that the USDA NASS definition of Pasture land has no direct relation to a FAO land use category.

Relating to Chinese national statistics:

Cultivated land ~ Temporary crops + Permanent crops

FAO forest definitions

Forest = Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds *in situ*. It does not include land that is predominantly under agricultural or urban land use.

Above ground biomass = All living biomass above the soil including stem, stump, branches, bark, seeds and foliage.

Roundwood = The total harvest of wood in forests.

Industrial roundwood = The amount of wood harvested for further processing in wood industries.

Wood fuel = The amount of wood used for energy purposes, covers fire wood, wood chips and roundwood for energy.

Roundwood = Industrial roundwood + Wood fuel.

Literature and statistical databases present data in different units, not all SI. We use the following conversions:

1 acre = 0.4047 Ha

1 lb = 0.45359 kg

1 hundredweight = 100 lb = 45.359 kg

1 bushel barley = 48 lb = 21.7724 kg barley (Murphey, 1993)

1 bushel maize = 56 lb = 25.4012 kg maize (Murphey, 1993)

1 bushel wheat, soy bean or rape seed/canola = 60 lb = 27.2155 kg (Murphey, 1993)

1 BTU = 1.055056 KJ (Cengel et al., 2008)

1 Mtoe = 41.868 PJ (IEA, 2007)

$\varrho_{ethanol} = 0.789$ g cm^{-3}

Abbreviations used in equations presented in the report:

A = Area allocated to a given crop
CP = Crop production
Y = Agricultural crop yield
RPR = Residue to product ratio
ARP = Agricultural residue production
RP = Round wood production
IRP = Industrial round wood production
WFP = Wood fuel production
I = Forest increment
PFP = Potential forest production
C = Relative amount of components (cellulose, hemicellulose and lignin) in agricultural and forestry resources
CPO = Component potential
MC = Moisture content
FW = Fresh weight
DW = Dry weight
VC = Volume contraction when wood is dried
r_0 = Wood density in dry state
i = country/region/province/state
j = crop
k = plant component