chaire modélisation prospective au service du développement durable

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Working Paper
N°2016-03-21

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Abstract

This report presents the methodology investigated in order to make more suitable and relevant the representation of bioenergy resources in the long term bottom up optimization model, TIAM-FR. Indeed, the current simplified representation is not suitable for distinguish different use for each proper bioenergy source. Furthermore, considering the important role of global bioenergy trade in energy system particularly for projecting future energy system, disaggregation of these resources appears as an essential requirement. In this study, based on the complementary purpose of improving the description of the bioenergy chain as well as the necessity of re-estimation of potentials, we focused on development of energy crops and woody biomass chains rather than Industrial wastes, municipal wastes, and landfill gas, which are not currently being traded intra regions for energy uses. In the case of energy crops, otherwise, the higher disaggregation will allow apply crop-specific biofuel policies as limiting the use of edible sources for energy purpose to avoid eventual conflicts with food security issues.

Keywords

Biomass Potential, Energy system, Long-term modelling, TIAM-FR

Acknowledgements

This research was supported by the Chair Modeling for sustainable development, driven by MINES ParisTech, Ecole des Ponts ParisTech, and AgroParisTech, supported by ADEME, EDF, GRTgaz, SCHNEIDER ELECTRIC and the French Ministry of Ecology, Sustainable Development and Energy.

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1- Introduction

In TIAM-FR model, the current representation simplifies bioenergy sources and facilitates bioenergy chain formulation. More precisely, primary bioenergy sources are presented in 8 commodities; 3 types of solid biomass according to price levels (MINBIOSLD0, MINBIOSLD1, MINBIOSLD2), 1 type of landfill gas (MINBIOGAS0), 1 type of industrial wastes (MINBIOBIN0), 1 type of municipal wastes (MINBIOBMU0), 1 type of bio liquid (MINBIOLIQ0), and 1 type of energy crop (MINBIOCRP0). However, this aggregation level is not suitable for distinguishing different use for each proper bioenergy source. In addition, global bioenergy market is in rapid development phase not only for production for domestic consumption but also for international trade. Table 1 shows the trade flow of bioenergy for bioethanol, biodiesel, and wood pellets from different sources and years depending according to data availability. Global bioenergy trade is estimated to be more than 2.9 EJ by 2011 and about 5% of total primary energy supply (549 EJ) in 2011. These results show the important role of global bioenergy trade in energy system and the fact that bioenergy trading is not negligible for projecting future energy system. Currently, TIAM-FR model does not include trading scheme of bioenergy but only for conventional fossil energies. For implementation of global bioenergy trade, disaggregation of bioenergy sources is an essential requirement. As regard the current aggregation level of bioenergy in TIAM-FR, different forms of woody biomass are not specified and are aggregated in one commodity, BIOSLD, despite a variety of woody bioenergy as wood pellets, fuelwood, charcoal, wood chips, and residues. Furthermore, bioenergy trade may be performed on the level of primary sources, for example, bulk roundwoods and raw crops over transformed biomass as biofuels, wood pellets. The table 1 shows also the significant share of indirect trade in global bioenergy market, which indicates exchange of raw materials for bioenergy (sugar cane itself for domestic bioethanol production, saw dusts for transforming in wood pellets and etc.). Hence, the disaggregation of bioenergy commodities of TIAM-FR model into more specific raw material levels is a key step to reflect the avenue of energy system evolution, more precisely, bioenergy pathways.

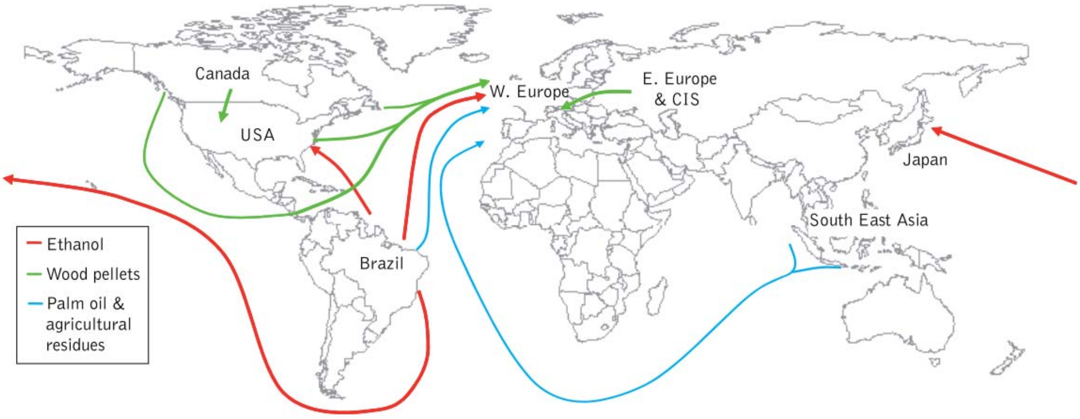


Figure 1. Global bioenergy trade flow (adopted from IEA bioenergy [1])

	Trade volume	Base year	Main Trader	Source
Bioethanol	127 PJ	2011	Brazil, China, USA, Europe, Japan	FAPRI [2]
Biodiesel	88 PJ	2011	Argentina, USA, Malaysia, Indonesia	
Wood pellets	167 PJ	2012	Europe, Canada, USA	M. Junginger et al. [3],FAOSTAT [4]
Fuelwood	82 PJ	2011	Europe, Southern Africa, Canada, USA	FAOSTAT [4]
Charcoal	20 PJ	2006	N/A	IEA [1]
Vegetable oils and seeds	>60 PJ	2006	EU, Argentina, Malaysia, Indonesia	IEA [1]
Industrial roundwood	1165 PJ	2011	Europe, China, India, Canada, Malaysia	FAOSTAT [4]
Wood chips and particles	635 PJ	2011	Europe, Vietnam, Thailand, USA, Canada, Russia, Indonesia, Australia and New Zealand	FAOSTAT [4]
Indirect trade	630 PJ	2006	N/A	IEA [1]
Total	2974 PJ			

In this study, based on the purpose of effectuating global bioenergy trade in TIAM-FR model, and improving bioenergy chain description as well as the necessity of re-estimation of potentials, we focused on development of energy crops and woody biomass chains rather than Industrial wastes, municipal wastes, and landfill gas, which are not currently being traded intra regions for energy uses. In the case of energy crops, current rough level of disaggregation does not allow apply crop-specific biofuel policies as limiting the use of edible sources for energy purpose to avoid eventual conflicts with food security issues. For example, Indian and Chinese government implemented regulations to restrict the use of sugar cane and oil seeds. However, the current structure, which refers to one aggregated commodity of energy crops, is not capable of managing crop-specific features. Moreover, energy crops chain in TIAM-FR model links simultaneously the single energy crops commodity to both bioethanol and biodiesel conversion processes as well as to use as solid biomass (see figure 2). Then, this structure has mixed energy crop potentials for both bioethanol, which intakes sugar/starch crops and biodiesel, which intakes oil bearing crops, then, may bring unrealistic results of projection. In addition, 2nd generation of bioethanol is set to take only energy crops excluding any other cellulosic materials, for example, agricultural residues. These identified weaknesses of the current structure are addressed in this study by reformulating energy crops energy chain as well as detailed disaggregation of primary energy crops.

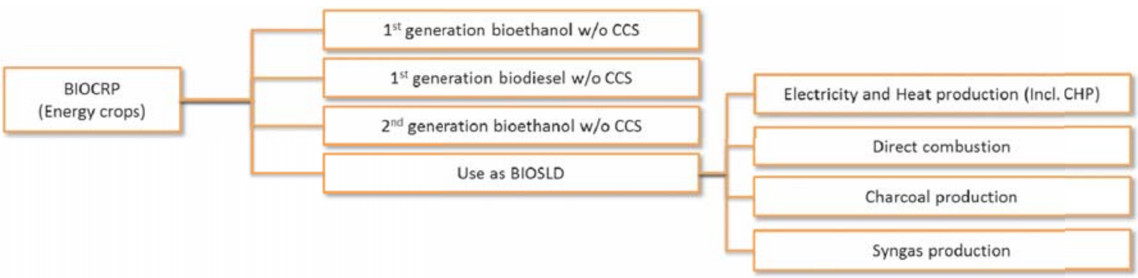


Figure 2. Overview of current energy crops chain in TIAM-FR

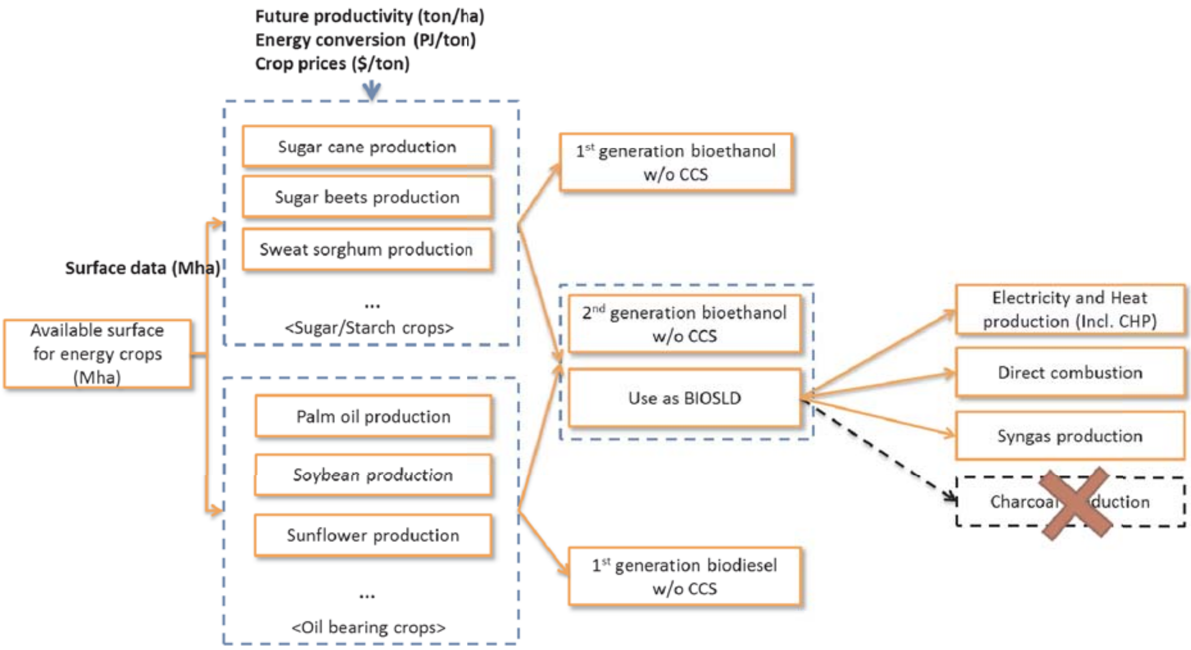


Figure 3. New structure for energy crops chain

To distinguish different types of energy crops and following conversion processes, surface-based structure is developed (see figure 3). Firstly, the total surface data is given to model, and it acts as the upper limit of the sum of surfaces of each selected crop. Secondly, the allocated surfaces for each crop are converted into energy unit with taking crop-specific productivity and assumed crop price as well as energy conversion rate, which is differentiated by water and energy content level. Thirdly, selected sugar/starch crops may be taken by followed energy transformation processes including uses as solid biomass except for 1st generation of biodiesel production. On the contrary, oil bearing crops exclude only 1st generation of bioethanol production. In addition, charcoal production process is eliminated in energy crop chain as it takes woody biomass as raw material rather than crops. This new scheme gives an endogenous choice of bioenergy crops and corresponding energy transformation process through optimizing the entire energy system cost. Also, it enables to implement bioenergy trade in raw material level as well as final energy form.

Likely to energy crops, solid biomass has also a simplified and aggregated energy chain in TIAM-FR. The type of primary biomass solid (roundwood, forestry and agricultural residues) is distinguished only by assumed three price levels and aggregated in to one commodity called as “BIOSLD”, which serves different conversion processes. It should be noted that this structure may bring a significant error on the available biomass solid for various conversion process and end-uses. For example, charcoal production cannot be effected from saw dusts, small wood particles, and agricultural residues, but, this structure allows using a variety of solid biomass in this process. Hence, further classification is highly required to procure more precise projection results.

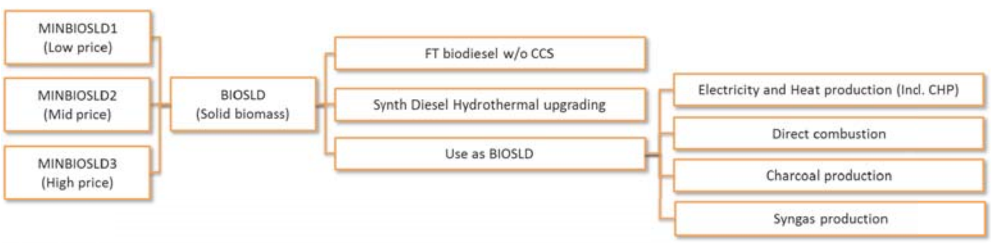


Figure 4. Overview of current solid biomass chain in TIAM-FR

As results, new structure of solid biomass is proposed along with energy crops. This new feature distinguishes 4 types of solid biomass; wood supply, wood processing residues, logging residues, and agricultural residues. In terms of conversion process, wood pellet production process is newly implemented and linked to processing residues and wood supply. Also, biogas production by anaerobic digestion is introduced with taking wood supply, logging residues and agricultural residues as inputs. Charcoal production process is disconnected with previous improper sources and takes only roundwoods from wood supply. Furthermore, agricultural residues are considered as one of the sources of 2nd generation of bioethanol (cellulosic ethanol plants) production. Consequently, this figure enables now to observe wood pellets trade, which represents the largest trading commodity as well as the largest traded primary source (round woods).

These propositions of new disaggregation of bioenergy sources and modified energy conversion processes for both energy crops and solid biomass require re-evaluation of commodity–specific potential. In this study, we identified 316-435 EJ/yr of energy crops potential and 38-49EJ/yr of woody biomass potential at a global scale by 2050. Comparing with total primary energy supply level (549 EJ) in 2011, bioenergy may answer to about 90% of TPES in the world. This estimation shows the importance of bioenergy deployment in a long-term projection.
In the following sections, we described the developed methodologies to estimate bioenergy potentials and following results through different scenarios.

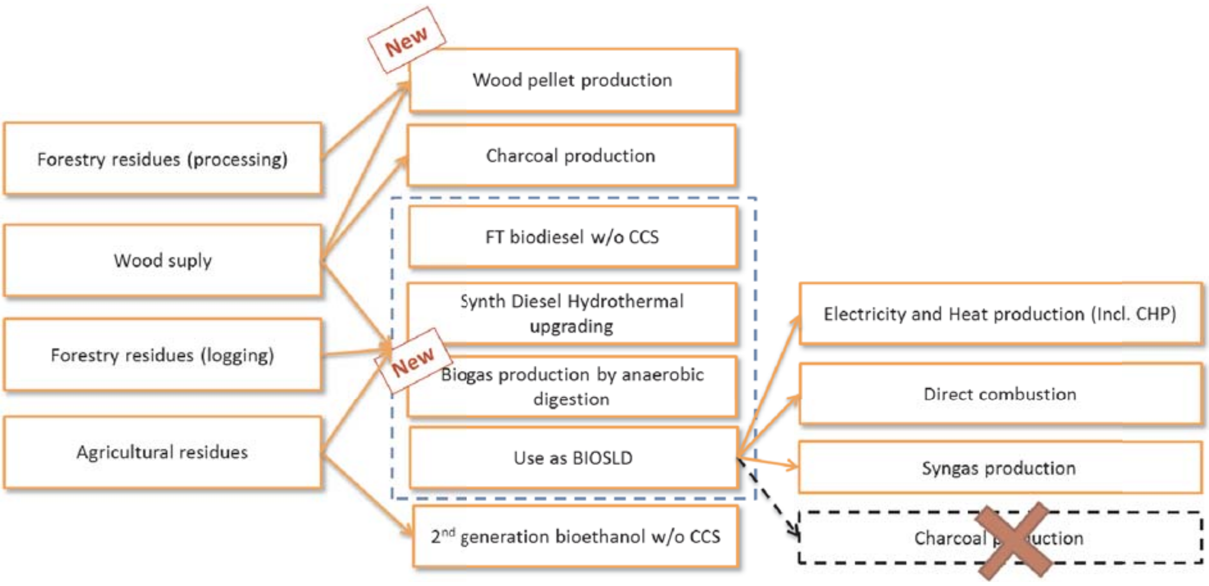


Figure 5. New structure of solid bomass chain

2- Bioenergy from agriculture

Agricultural bioenergy refers to energy crops, which means sugar and starch crops, oil-bearing crops, and agricultural residues. In this chapter, global bioenergy potential assessment has been made for each region aggregated and presented in TIAM-FR model. In the world, land is limited resource and then, bioenergy production from agricultural products may bring competition with food supply. In this study, bioenergy production from agricultural lands avoids possible competition with food at most.

2-1- Methodology

To estimate bioenergy potential from agricultural products, food-first approach is applied. This approach gives a priority on responding firstly to food demand and allocating adequate land for food production. The concept of this approach has been previously applied in a study of Smeets et al [5]. In this study, we limited land types, which are available for bioenergy production only on "current cultivated land" and "grass and other wooded land" following by land classification of GAEZ (Global Agro-Ecological Zones, from FAO) assessment. The estimation methodology composed by several steps. Firstly, land required for food production is estimated based on food demand and population projection. Secondly, the expansion of infrastructure land (Built-up land) is estimated based on current built-up land occupation rate per capita and population projection. In our estimation, the deforestation for agricultural land expansion for both purposes of food production and bioenergy production is not allowed for all projection years.

The main formula of land availability is expressed as follows:

$$Landavl_{i,j} = Agrland_{i,baseyear} + Grassland_{i,baseyear} - Agrland_{i,j} - livestockland - builtupexp_{i,j}$$

Where:

$Landavl_{i,j}$: $available\ land\ for\ bioenergy\ production\ in\ region\ i\ and\ year\ j$

$Agrland_{i,baseyear}$: $Agricultural\ land\ in\ region\ i\ and\ baseyear$

$Grassland_{i,baseyear}$: $Grass\ and\ other\ wooded\ land\ in\ region\ i\ and\ baseyear$

$Agrland_{i,j}$: $Agricultural\ land\ required\ in\ region\ i\ and\ year\ j$

$Livestockland_{i,j}$: $Land\ required\ for\ livestock\ production\ in\ region\ i\ and\ year\ j$

$Builtupexp_{i,j}$: $Estimated\ builtup\ land\ expansion\ in\ region\ i\ and\ year\ j$

$if\ (Builtupland_{i,j} - Builtupland_{i,baseyear}) < 0, \qquad Builtupexp_{i,j} = 0$

$unless, Builtupexp_{i,j} = Builtupland_{i,j} - Builtupland_{i,baseyear}$

$i = projection\ year$

$j = region\ or\ country$

Each type of required land estimation is described in the following sections from 2.1.1 to 2.1. .

2-1-1 - Food demands by 2050

Future food demands are estimated based on future diet evolution from FAO's recent publication "World agriculture: towards 2030/2050 Prospects for food, nutrition, agriculture and major commodity groups" (hereafter referred as "WAT") [6] and United Nations' population projection[7] for each country. In FAO's publication on world diet evolution, diet evolution is estimated per regional aggregates, which divide the world in "Sub-Saharan Africa", "Near East/North Africa", "Latin America and the Caribbean", "South Asia", "East Asia" and "Developed countries". Hence, to estimate future food demand per country, diet evolution per commodity groups was firstly disaggregated into country level and multiplied by population projection. In addition to region disaggregation, it is required to disaggregate the commodity groups presented in FAO's diet evolution estimation. All food commodities were aggregated in 8 groups as cereals, roots and tubers, sugar and sugar crops, pluses, vegetable oils, meat, milk and dairy, and other food. And these aggregated food commodity groups were disaggregated based on current composition ratio of food consumption published in food balance sheet (FBS) of FAO [4].
The general methodology to estimate total food consumption quantity is expressed as follows:

$$Group\_commodity_{i,reg,year} = \sum commodity_{j,reg,year}$$

$$Commodity_{j,reg,year} = Group\_commodity_{i,reg,year} \times \frac{commodity_{j,reg,baseyear}}{Group\_commodity_{i,reg,baseyear}}$$

Where:

$Group\_commodity_{i,reg,year}$ = Consumption of commodity group i in corresponding region and year

$commodity_{i,reg,year}$ = Consumption of commodity j , which belongs to commodity group i in corresponding region and year

Along with general estimation methodology, food self-sufficiency ratio is applied at the end of the food demand estimation to derive domestic production of each commodity. Based on FBS statistics, self-sufficiency ratio (SSR) is calculated from production quantity, import quantity, and export quantity of base year and assumed to be constant to time horizon. The equation of SSR estimation is referred from FBS handbook and expressed as follows [8].

$$SSR = \frac{Production}{Production + import - export} \times 100$$

In FBS, utilization of food commodity is classified in 6 categories, as food, food manufacture, feed, seed, waste, and other uses. Consumption for food purpose is the sum of food and food processing in most of commodities except for the commodity, which presented both in processed products and crops, for example, sugar with sugar cane. In this case, processed quantity from original crops is excluded and reallocation to final product is assumed. For certain processed food commodities as sugar, vegetable oils, milk and dairy, and rice, which do not correspond with general methodology, supplementary unit matching had to be complied. In the case of estimating seed and waste amount, the proportion between "seed and waste" and "food and processing" of baseyear for each region and commodity is compiled and applied to the time horizon due to the lack of information and difficulty of projecting changes in the future. However, the share of "seed and waste" mostly remains very insignificant (less than 1%) and not enough to change the picture of future demands. The specific features of our estimation are described in following sub-sections.

2-1-1-1- Rice estimation

In the case of rice, annual consumption data is presented in milled equivalent while the productivity data is expressed in paddy. According to guideline of "Food balance sheet", 67% of conversion rate is assumed to estimate milled equivalent weight from paddy rice. Hence, the inversed conversion rate is applied to estimate paddy rice consumption quantity in the future.

2-1-1-2- Sugar crops estimation

Regarding sugar consumption, FBS presents sugar consumptions distinguishing sugar products and sugar crops, thus, they are estimated sugar crops in crops weight and sugar in sugar weight. On the other hand, FAO's estimation on diet evolution expressed sugar and sugar crops consumption in sugar raw equivalent unity. Similarly to rice conversion stage, conversion rates from sugar crops to sugar products, of which 11% for sugar cane and 15% for sugar beet imposed, are retrieved from FBS guideline. Hence, the total sugar consumption is disaggregated by following equation. In addition, it should be noted that the sugar consumption quantity should be recalculated by using self-sufficiency ratio, which excludes imported sugar quantity, to estimate domestic sugar crops amount used in sugar transformation.

$$Sugar_{total,year} = Sugar_{raw,year} + Sugarcane_{food,year} \times 0.11 + Sugarbeet_{food,year} \times 0.15$$

$$Sugar_{raw,year} = Sugarcane_{proc,year} \times 0.11 + Sugarbeet_{proc,year} \times 0.15$$

This equation expresses the estimation of sugar crops consumption from WTA's future diet evolution. In our calculation, two assumptions were made. Firstly, the proportion between the quantity of sugar crops used in processing and direct sugar consumption maintains to time horizon from base year. Secondly, the proportion between sugar cane and sugar beet used in processing remains constant as well as the proportion of direct food consumption between those two sugar crops.

Ratio between sugar and sugar crops consumption:

$$\frac{Sugar_{raw,baseyear}}{Sugarcane_{food,baseyear} \times 0.11 + Sugarbeet_{food,baseyear} \times 0.15} = \frac{Sugar_{raw,year}}{Sugarcane_{food,year} \times 0.11 + Sugarbeet_{food,year} \times 0.15}$$

Ratio between sugar crops for processing and direct consumption:

$$\frac{Sugarcane_{proc,baseyear}}{Sugarbeet_{proc,baseyear}} = \frac{Sugarcane_{proc,year}}{Sugarbeet_{proc,year}}$$

$$\frac{Sugarcane_{food,baseyear}}{Sugarbeet_{food,baseyear}} = \frac{Sugarcane_{food,year}}{Sugarbeet_{food,year}}$$

2-1-1-3- Oil crops estimation

In the line with sugar crops estimation, the estimation on vegetable oils and oil crops, which is made by WTA, is aggregated in one group commodity with oil equivalent unity. Hence, two disaggregation phases were developed. Firstly, the aggregated vegetable oil consumption is divided into oil and oil crops consumptions. For this phase, the proportion between oil crops consumption for food and vegetable oils consumption for food and processing, based on FBS's baseyear data, was estimated. and are the corresponding varaibles and expressed in following equations.

$$Agr\_oil\_adj_{region,year} = Agr\_oil_{year} \times \frac{\sum oil\_conso_{region,baseyear}}{\sum oil\_conso_{i,region,baseyear} + \sum oilcrops\_food_{i,region,baseyear} \times a_i}$$

$$Agr\_oilcrops\_adj_{region,year} = Agr\_oil_{year} \times \frac{\sum oilcrops\_food_{i,region,baseyear} \times a_i}{\sum oil\_conso_{i,region,baseyear} + \sum oilcrops\_food_{i,region,baseyear} \times a_i}$$

In addition, each oil crops data needs to be converted into vegetable oil equivalent data. In FBS' handbook, oil conversion rates for certain oil crops are presented. For the rest of oil crops, external researches[9][10] completed the list of conversion rates (See table 2).

Oil crops	Conversion ratio	Source
Palm	0.225	GAEZ assessment
Soybean	0.17	Gressen
Sunflower	0.44	Gressen
Rapeseed	0.4	Gressen
Jatropha	0.38	Gressen
Groundnut	0.45	FAO
Cotton	0.18	FAO
Olives	0.15	FAO
Coconuts	0.123	FAO + own calculation using copra and copra oil conversion
Sesame and others	0.3	Average data

Table 2. Oil conversion rate for oilcrops

Secondly, each readjusted oil crops and vegetable oils consumption data go through the re-allocation phase for estimating individual consumption of each oil crops commodities. This reallocation process is based on each commodity share in total oil crops of baseyear.

$$Oil_{i,region,year} = Agr\_oilcrops\_adj_{region,year} \times \frac{Oil_{i,region,baseyear}}{\sum Oil_{j,region,baseyear}}$$

$$ilcrops_{i,region,year} \times a_i = Agr\_oilcrops\_adj_{region,year} \times \frac{Crop_{i,baseyear} \times a_i}{\sum Crop_{j,baseyear} \times a_j}$$

2-1-1-4- Milk and dairy

Milk and dairy consumption is also aggregated into one group commodity in WTA's estimation. It needs only conversion of cream to milk because the cream consumption is limited only to direct food purpose. 35% of Cream extraction rate from milk is retrieved from the guideline on the preparation of supply/utilization accounts (SUAs) published by FAO [11]. The disaggregation steps are expressed in the following equations. In the first step, cream consumption of base year is converted to milk equivalent unit using cream extraction rate to estimate aggregated milk and dairy consumption. In the second step, the future demand of each commodity is calculated by using the proportion between cream and milk consumption of base year.

$$Milkdairy_{base} = \frac{cream_{base}}{0.35} + milk_{base}$$

$$Milkdairy_{year} = \frac{cream_{year}}{0.35} + milk_{year}$$

$$\frac{cream_{year}}{0.35} = milkdairy_{year} \times \left(\frac{\frac{cream_{base}}{0.35}}{Milkdairy_{base}}\right)$$

$$milk_{year} = milkdairy_{year} \times \left(\frac{milk_{base}}{milkdairy_{base}}\right)$$

2-1-2- Projection on feed demand by 2050

Recently, the increasing demands of meats products became one of the major drivers for agricultural land use. In addition, the growing livestock productions lift up the agricultural production as well as corresponding land uses. According to FAO's recent report [6], livestock production is identified as the world largest land user by grazing and production of fodder and feed grains. On the other hand, required land for livestock products depends on the efficiency of production and production system. Currently, no global database as FAOSTAT provides such data in global coverage. However, some studies [5], [12] attempted to identify these parameters either to explore the evolution of livestock production system or to estimate bioenergy potentials. In these studies, three different ways of livestock production were proposed as pastoral system, which grazes livestocks mostly from pastures and fodder crops, landless system, which feeds the animals only from feed crops and residues, mixed system, which combines those two systems. Also, three different feed compositions, which are "grasses and fodder", "feed crops", and "residues", are identified. In order to estimate final demand of animal feed for each type, the following equation, which was previously developed by Smeets [5], was reformed in this study.

$$Feed_{i,year,region} = Demand_{j,year,region} \times Fco_{i,j,prod} \times Fce_{j,prod}$$

Where Feed is the final estimation of each animal feed type i, of which 3 compositions are described above, for projection year and for specific region. is the meat demands estimated from previous section for meat type j, which includes meat, milk, mutton and goat meat, pig meat, and poultry meat, for projection year and specific region. is the feed composition for each meat type i and feed type j for production system "prod". This parameter is the share of each feed category in total demand for animal feed. is the feed conversion efficiency for each meat type and production system and expressed in the amount of feed demands (kg DM) per the amount of animal products production (kg animal product).
In our study, we included two livestock systems, i.e. "Landless" and "Mixed" system. "Pastoral" system is excluded under estimation of technological progress and also by the reason that pastoral system has too low land/product efficiency to fulfil the fast growing demand of meats in the future. The data on feed composition is collected from two previous studies [5], [12] (see table 3). In case of feed conversion efficiency, mixed and landless systems are assumed to have the same feed conversion efficiency due to the saturation of efficiency improvement. In our study, the highest level of feed conversion efficiency, which was estimated in [12] for 2030, is applied to the end of time horizon for all regions and for both landless and mixed system.

PROD	Animal Products	Grasses/Fodder	Feed Crops	Agri Residues
LANDLESS	Bovine	0	0,8	0,2
	Dairy products	0	0,8	0,2
	Mutton and goat	0	0,75	0,25
	Pig	0	0,75	0,25
	Poultry	0	0,75	0,25
MIXED	Bovine	0,5	0,3	0,2
	Dairy products	0,5	0,3	0,2
	Mutton and goat	0,85	0,1	0,05
	Pig	0	0,75	0,25
	Poultry	0	0,75	0,25

Table 3. Feed composition for each animal product

Prod	Bovine	Dairy products	Sheep/goat	Pig	Poultry
Landless,Mixed	15	1.2	17	6.2	3.1

Table 4. Feed conversion efficiency (kgDM feed/kg animal product)

In final steps to estimate feed demands, disaggregation of each feed type to detailed commodity was addressed instead of estimating aggregated feed products yields. Firstly, it is assumed that grasses and fodder crops are composed of two commodities as alfalfa and grass. Actually, natural pasture grazing is extremely complicated to estimate its productivity due to the large variation between localizations. Furthermore, data on pasture grazing at a global coverage is not available. Hence, alfalfa and grasses are treated as main fodder crops in this study. Nowadays, alfalfa is being considered as more attractive fodder crops due to their low moisture content compared to grasses. The dry matter conversion factors are estimated about 0.89 for alfalfa and 0.2 for normal grasses [13–15]. A fraction of composition between alfalfa and grass is assumed and applied except for the regions where alfalfa production does not appear, in this case, fodder crops contain only grasses. Secondly, detailed commodities in grouped feed crops are estimated based on food balance sheet of base year. The composition and share of each feed crop are maintained to the time horizon.

2-1-3- Projection on crops yields by 2050

In this study, we used the projection of crops yields from GAEZ assessment of the International Institute of Applied Systems Analysis (IIASA). GAEZ assessment provides the estimation on crops yields through different scenarios and different constraints. Firstly, agro-climatic yields are calculated in GAEZ biomass model, which reflects climatic constraints as temperature, radiation and moisture regimes as well as water stress regarding to crop production. Secondly, agro-ecological yields include soil fertility beyond climatic potentials. In addition, each constraint interacts with different emission scenario with regard to IPCC's scenario from A1 to B2. In our study, we assumed primarily A1 scenario, whose storyline describes a future world with fast economic growth and rapid introduction of new and efficient technologies. In the line with our assumption, corresponding socio-economic parameters, for example, demography profiles projected by United Nations [16] were collected and applied. In the case of productivity constraints, agro-climatic yields were used in priority and agro-ecological yields completed the future productivity for the crops, of which attainable yields are not contained in GAEZ assessment. Nevertheless, soil nutrient quality is not ignored but accounted in land availability calculations by limiting further land expansion on "grasses and other wooded land" following the level of soil nutrient quality. The land calculation phase will be explained in details in next section. In GAEZ model results on crops productivity, two different water systems are distinguished; "rain-fed" and "irrigation". Hence, the combination of these two productivities are realized under a fraction estimation between rain-fed and irrigation system. Furthermore, GAEZ model projects future productivity evolution for 2020 and 2050. As future food demands are projected for 2030 and 2050, the linear interpolation between 2020 and 2050 is included in our calculation for estimating the crops yields on 2030. As a result, following equation is developed to derive corps yields for each region and projection year.

$$Yields_{crops,region,year} = irri \times Yields_{irri,crops,region,year} + rain \times Yields_{rain,crops,region,year}$$

Where :

$Yields_{irri,crops,region,year}$ = Future yields for a specific crop in year,region with irrigation water system

$Yields_{rain,crops,region,year}$ = Future yields for a specific crop in year,region with rain-fed water system

$irri$ = a fraction of irrigation system in total agriculture production

$rain$ = a fraction of rain-fed system in total agriculture production

$rain + irri = 1$

Also, detailed information on crops yields data applied in this study is described in table 5. This table shows the commodity matching notes between future food demand and available crops yields data and the status of data existence on GAEZ assessment.

Gaez data status (agro climitally attianable yield)					note	FAO stat
Commodity	2020 rain-fed	2050 rain-fed	2020 irrigated	2050 irrigated		
Rice	a	a	a	a	Agri ecological wetland rice yield applied (on current cultivated land)	o
Wheat	o	o	x	o		o
Barley	a	a	a	a		o
Maize	o	o	o	x		o
Rye	o	o	a	a		o
Oats	o	o		o		o
Millet	o	o	o	o	«Foxtail millet»	o
	o	o	o	x	«Pearl millet»	
Sorghum	o	o	o	o		o
Cassava	o	o	o	x		o
Potatoes	o	x	x	o	«White potatoes»	o
Sweet Potatoes	o	o	o	o		o
Yams	o	x	o	o		x
Roots, other	x	x	x	x	Application of potatoes	x
Beans	o	o	x	o		o
Peas						o
	o	x	o	o	«Dry peas»	
	o	o	o	x	«Chickpea»	
	o	o	o	o	«Pigeon pea»	
	x	o	x	o	«Green gram»	
Pulses, other	x	x	x	x	Application of peas	x
Sugar cane	o	x	x	o		o
Sugar beet	o	o	x	o		o
Soybeans	o	o	o	o		o
Groundnuts	o	x	a	a	Agro ecological yields	o
Sunflower	o	x	a	a	Agro ecological yields	o
Rape	o	o	x	o		o
Cotton	o	o	x	o		o
Coconut	o	o	o	o		o
Sesame	x	x	x	x	Element does not exist (ratio of rape, sunflower, groundnuts) one or three applied	o
Palm	o	o	o	o	FAO palm yield = fruit yield	o
Olives	o	o	o	o		o
Oil crop other	x	x	x	x		x

Table 5. Detailed information on application of productivity data

2-1-4- Projection on land availability by 2050

In this study, the land classification of GAEZ assessment, which divides the land cover in cultivated land, grass land, built-up area, forest land, and other non-productive land (barren and sparsely vegetated), was applied. By using food-first approach, required land use for food and feed demand is firstly allocated to the total surface of cultivated land and grass land. Then, the rest of grass land is considered as suitable for bioenergy crop production. Current forest land is completely conserved from other uses. In addition, the protected area on grass land is also conserved in our estimation for the aspect of sustainable development.

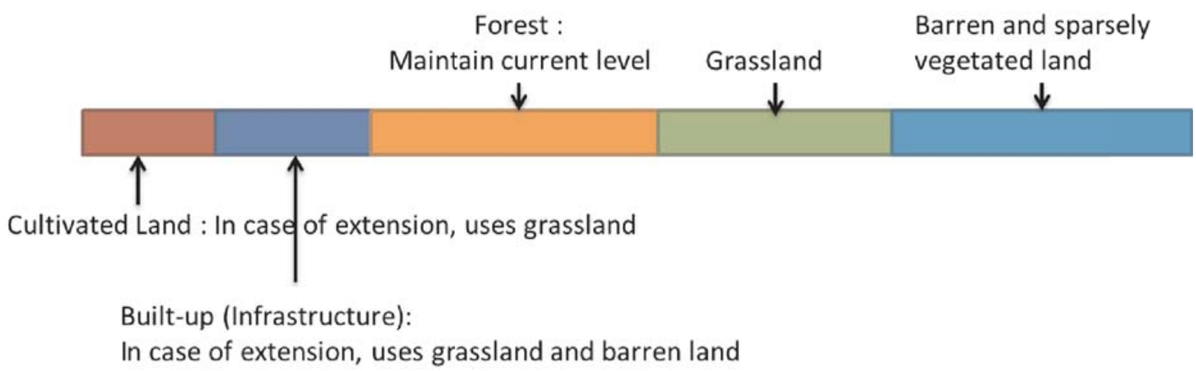


Figure 6. Land classification and brief in future land allocation

In the first step, built-up area is projected to time horizon for each region. Based on land occupation per capita of reference year, future built-up area is calculated by multiplying demographic information. Then, the expansion of built-up area spanned to grass land and barren land following the proportion between two surfaces of reference year.

$$\textit{Built-up land}_i = Pop_i \times (\textit{Built-up}_{base} / Pop_{base})$$

In the second step, the change in agricultural land is estimated for each region and projected year using crops yields and food demands. In this case, extension is allowed only on current cultivated land and grass land.

Also, fodder land required for animal products is estimated for each region using fodder crops demand data and corresponding fodder crops yields. Fodder land use is allocated only on grass land.

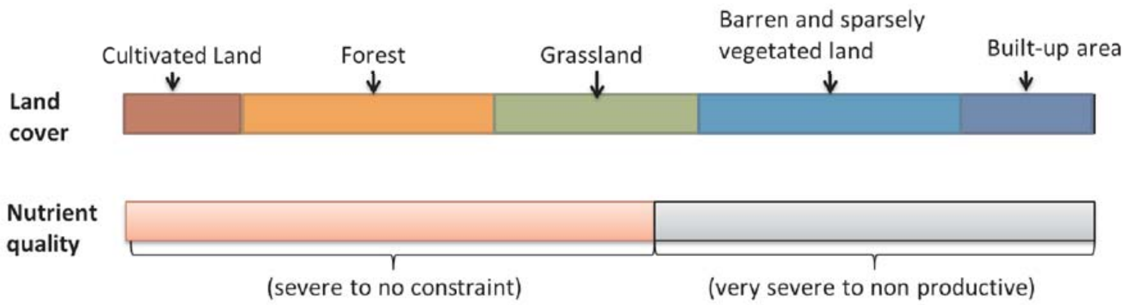
$$Fodderland_{year,region} = \sum Foddercrops_{crp,year,region} / yield_{crp,year,region}$$

As results, first estimated land availability becomes the rest of grassland after extracting the surface amount required for animal feeds and food production and can be expressed as follows.

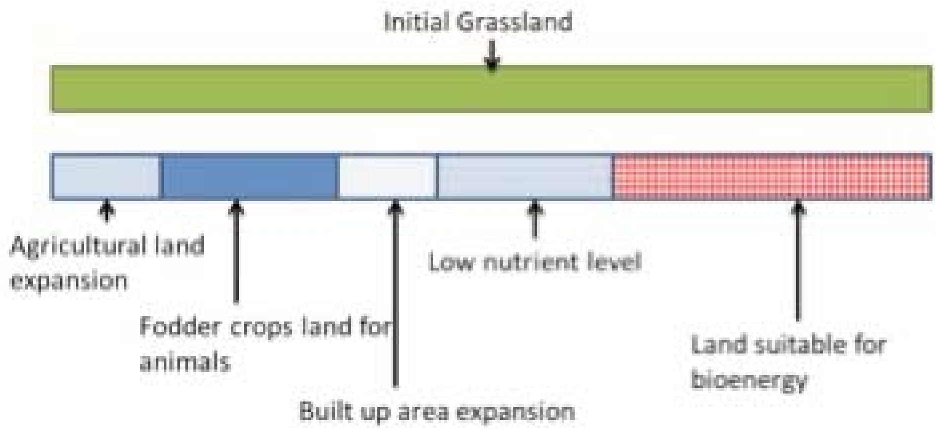
$$\begin{aligned} First\_Land\ available_{region,year} \\ &= Grassland_{region,baeseyear} - \Delta\ Agricul \\ &- Fodder\ land_{year,region} - Builtup\ exp \end{aligned}$$

$$\Delta\ Agricultural\ land_{year,region} = \sum Demand_{crp,year,region} / yield_{crp,year,region} - Demand_{crp,base,re}$$
$$yield_{crp,base,\ region}$$

However, as we applied crops yields under agro-climatic constraints not taking account of soil qualities, soil nutrient quality needs to be addressed for final estimation of land availability. In this context, the classification on soil nutrient quality of GAEZ assessment data was used to filtering once again our first estimated land availability. Soil quality level is defined from very severe for the least nutrient level to no constraint for abundant nutrient level. A range from severe to no constraint is applied in our calculation for the purpose of avoiding over-estimation on land availability.



Hence, along with grass land occupation from agricultural land expansion, fodder crops production, and built-up area expansion, low nutrient level area is extracted to estimate final available land for bioenergy production. The final land availability can be expressed as following diagram and equation.



$$
\begin{aligned}
&Final\ land\ available_{region,year} \\
&\quad = Grassland_{region,baeseyear} - \Delta\ Agricultural\ land_{year,region} \\
&\quad - Fodder\ land_{year,region} - Builtup\ exp_{year,region} \\
&\quad - Low\ Nutrient\ Grassland_{year,region}
\end{aligned}
$$

On the other hand, the countries in boreal zones required further treatment, because GAEZ assessment defined that soil quality in this area is evaluated not suitable for vegetation. Then, it resulted that the surface total, of which nutrient quality ranges from server to no constraint, is much less than the sum of cultivated land, forest land, and grassland. To avoid this underestimation, forest areas in boreal zone are added to complete total fertile surface. Following the assumption of no-forest area use for agricultural purpose, the total area of other wooded land in boreal zone was added to total nutrient surface for Russian federation, Alaska in US, Canada, Norway, Sweden, and Finland. The forest resource data of the boreal countries was collected from FAO's publication [17].

Forest category (million ha)	Former USSR	Alaska	Canada	Norway	Sweden	Finland
Forest and other wooded land	790	46	327	7	21.4	22.7
Closed forest	673	5	198	5.9	18.4	19.5
Exploitale closed forest	450	5	144	5.1	16.1	19

Table 6. Major categories of forest land within countries and within their boreal zones (FAO)

2-1-5- Agricultural residues

Agricultural residues are calculated based on region and crop-specific RPR (residue to product) ratio. RPR ratio is composed of two elements, firstly, harvest factor to estimate total crop residues, secondly, recovery factor to estimate collectable crop residues. Region and crop-specific RPRs are mainly retrieved from literatures [18],[19] and completed by SERI studies [20] for the missing elements. Agricultural residues are calculated by multiplying harvest factors and recovery rate to the amount of primary production for each region and crop as expressed in the following equation.

$$Residues_{comm,region,year} = Prod_{comm,region,year} \times RPR_{comm,region} \times Recovery_{comm,region}$$

Where :

$Residues_{comm,region,year}$ = Agricultural residues of comm in each region and year

$Prod_{comm,region,year}$ = Domestic production of comm in each region and year

$RPR_{comm,region}$ = Residue-to-Product Ratio of comm in each region

$Recovery_{comm,region}$ = Recovery ratio of comm in each region

Comm = commodity

The table 7 shows an example of harvest factor and recovery ratio applied in this study. For some commodities, region specific data is not available, then, global average is used. On the other hand, the removal of crop residues from soil is being argued because of the risk to deplete soil organic matter, degrade soil quality and fertility and soil erosion. Regarding to such environmental risks listed above, the maximum removal of crop residues should be avoided. According to our literature review on sustainable use of crop residues [5][21][22][23][24] , 25% or 50% of general crop residues could be removed without interfering environmental performance and 5% of recovery rate is assumed to be sustainable for vegetables and fruits. Hence, two upper bounds of residues recovery rate (25% and 50%) were set to 50% for general crops and 5% for vegetables and fruits over region and crop specific recovery rates.

Item	East Asia	East Europe	Latin America	North Africa / West Asia	North America / Oceania	South Asia / Central Asia	Subsaharien Africa	West Europe
Rice	0.5	0.6	0.6	0.6	0.6	0.75	0.75	0.6
Wheat	0.75	0.75	0.75	0.75	0.6	0.85	1.15	0.5
Barley	0.75	0.75	0.75	0.75	0.6	0.85	1.15	0.5
Maize	1.5	0.95	1.5	1.5	0.6	1.75	1.75	0.6
Rye	0.75	0.75	0.75	0.75	0.6	0.85	1.15	0.5
Oats	0.75	0.75	0.75	0.75	0.6	0.85	1.15	0.5
Millet	1.5	0.95	1.5	1.5	0.6	1.75	1.75	0.6
Sorghum	1.5	0.95	1.5	1.5	0.6	1.75	1.75	0.6
Cassava	0.4	0.2	0.4	0.4	0	0.4	0.4	0
Potatoes	0.5	0.25	0.5	0.5	0	0.5	0.5	0
Sweet potatoes	0.5	0.25	0.5	0.5	0	0.5	0.5	0
Yams	0.5	0.25	0.5	0.5	0	0.5	0.5	0
Roots, other	0.5	0.25	0.5	0.5	0	0.5	0.5	0
Beans	0.2	0.5	0.2	0.2	0	0.2	0.2	0
Peas	0.2	0.5	0.2	0.2	0.5	0.2	0.2	0.5
Pulses, Other	0.2	0.5	0.2	0.2	0.5	0.2	0.2	0.5
Sugar cane	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Sugar beet	0.35	0.125	0.35	0.35	0	0.35	0.35	0
soybeans	0.6	0.75	0.75	0.75	0.6	0.75	0.75	0.6
groundnuts	0.6	0.6	0.75	0.75	0.6	0.75	0.75	0.6
Oil crops, other	1.15	0.95	1.15	1.15	0.95	1.15	1.15	0.95

Table 7. Crop residues production ratio = RPR x Recovery rate

2-2- Results: Agricultural bioenergy potential

Based on the methodology described in previous section, agricultural bioenergy potential is estimated for 15 regions (Australia-New Zealand (AUS); Canada (CAN), United-States of America (USA), Western Europe (EU-15, Iceland, Malta, Norway and Switzerland, WEU), Eastern Europe (EEU), Japan (JPN), India (IND), China (includes Hong Kong, excludes Chinese Taipei, CHI), Africa (AFR), Central and South America (CSA), Middle-East (includes Turkey, MEA), Mexico (MEX), South-Korea (SKO), Other developing Asian countries (includes Chinese Taipei and Pacific Islands, ODA), Former Soviet Union (includes the Baltic states, FSU)), which correspond to region groups of TIAM-FR model.
In the case of bioenergy crops, the potential surplus land has been estimated for different scenarios. The tested scenarios consist of different proportion level of irrigation and rain-fed system levels, share of alfalfa in fodder crops, and animal production systems; landless and mixed system. Particularly water system evolution, which implies increasing share of irrigation system in cultivation, is limited to 80% of total cultivated land except for the countries, which currently equipped more than 80% of irrigation system; in this case, current irrigation system share is maintained to the time horizon. The water system of cultivation is set to evolve from each country's current share of irrigation system. Data on water system of each country, 'Area equipped for irrigation and percentage of cultivated land', was collected from AQUASTAT [25] of FAO for the reference year.
First scenario set is considered as maximum technology evolution which implies 40% of increase in irrigation system until 2050, 80% of alfalfa in fodder crops(2), and landless or mixed animal production system. Then, second scenario set decreases the irrigation system evolution to 30% and third scenario set to 20%. Each scenario set is calculated for two different animal systems (mixed and landless) along with the assumption of 80% alfalfa share in fodder crops.

Set no.	Scen no.	Water system	Animal production system	Alfafa vs grass
Set 1 : Maximum tech	Scen. 1-1	+40% in 2050	Landless	80% for alfalfa 20% for grass
	Scen. 1-2	+30% in 2050	Landless	
Set 2 : Medium tech	Scen. 2-1	+40% in 2050	Mixed	
	Scen. 2-2	+20% in 2050	Landless	
Set 3 : Low tech	Scen. 3-1	+30% in 2050	Mixed	
	Scen. 3-2	+20% in 2050	Mixed	

Table 8.Scenarios

As results (see table 9 and figure 7), Scen 1-1 showed the largest potential surplus agricultural land in 2050 of 3.1 Mha and land availability gradually decreases for the rest of scenarios up to 2.3Mha. The results show that animal production system largely effects on agricultural land demand in the Middle East Asia (MEA), India (IND), Japan (JPN), and Africa (AFR). Comparing two scenarios, scen 1-2 and scen 3-1 with moderate water system evolution and different animal production system, those regions state a sharp drop in available surface for bioenergy production to 115% for MEA, 228% for IND, 76% for JPN, and 67% for AFR. These results are originated from low pasturage productivity, less eligibility of alfalfa production, and exponential increase in demands of animal products with diet and population evolutions.

(2) Alfalfa share imposition is applied only for the countries, which currently have alfalfa production. It is assumed that alfalfa production is not eligible for non cultivating countries in 2010.

Region	Scen 1-1	Scen 1-2	Scen 2-1	Scen 2-2	Scen3-1	Scen 3-2
MEA	87	85	79	0	0(-13)	0(-22)
USA	229	224	214	219	211	206
JPN	3	3	3	1	1	1
EEU	35	35	34	34	33	33
CHI	247	243	235	235	228	223
CSA	403	401	395	403	398	395
AUS	449	447	442	454	449	447
FSU	678	674	662	642	632	626
WEU	60	58	53	59	55	52
IND	3	0(-4)	0 (-19)	5	0(-12)	0(-23)
ODA	71	68	62	59	54	51
SKO	1	1	1	1	1	1
MEX	80	79	77	72	69	67
AFR	656	649	631	328	215	77
CAN	174	173	171	175	174	174
World	**3175**	**3136**	**3041**	**2687**	**2494**	**2307**

Table 9. Potential surplus agricultural land in Mha for 2050

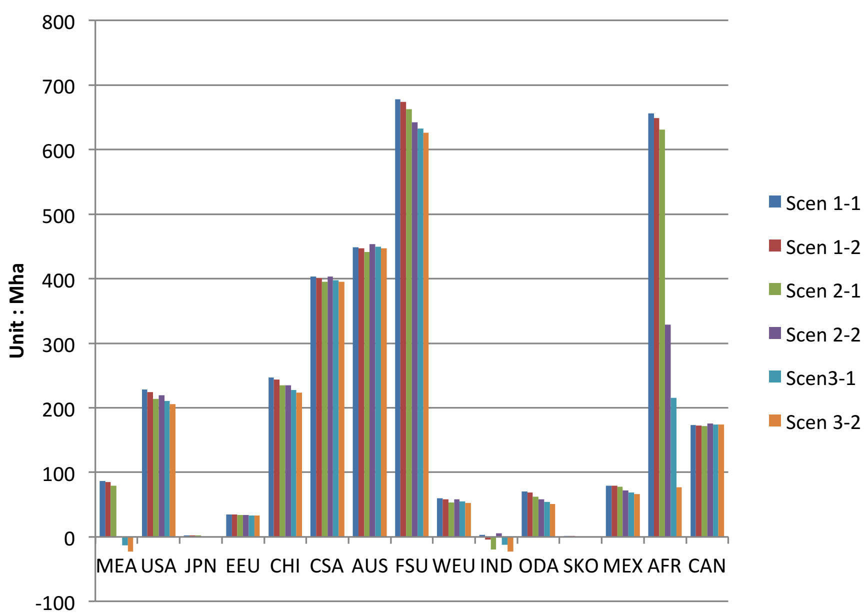


Figure 7. Potential surplus agricultural land by region in 2050

According to our new structure of bioenergy scheme in TIAM-FR model, available surplus agricultural land data will be directly entered to model and new energy unit conversion processes convert each surface for internally chosen commodities. However, in this report, bioenergy potential from energy crops is simply pre-estimated based on available surface, global average of productivity (7.5 – 12.6 tDM/ha) [26,27], and gross calorific value of 18.3MJ/kgDM [18]. Figure 8 shows bioenergy potential from energy crop production on surplus agricultural land by 2050. This graph illustrates bioenergy potential from middle level scenario, scen 3-1 (30% increase of irrigation system with mixed animal production system) and also the minimum and maximum level among 6 developed scenarios.

As results, global agricultural bioenergy potential varies between 316 EJ/yr and 435EJ/yr by 2050. With the comparison to other studies, the estimated range of bioenergy potential from agriculture places less than the studies of M.Hoogwijk et al. (8 – 1098EJ) [23] and Smeets et al. (215-1272EJ) [5] and higher than the results of Erb et al.(28-128EJ) [28] and WBGU (34-120EJ) [27]. Different results of other studies originally come from several assumptions as projections of diet evolution, population, land use types, cultivation productivities, heating values of crops, and so on. Particularly, recent study of M.Hoogwijk, 2005 examined bioenergy potential from energy crops under climate scenarios (SRES) of IPCC. Likely, out study is basically based on scenario A1, which conforms to socio-economic assumptions introduced in TIAM-FR model.

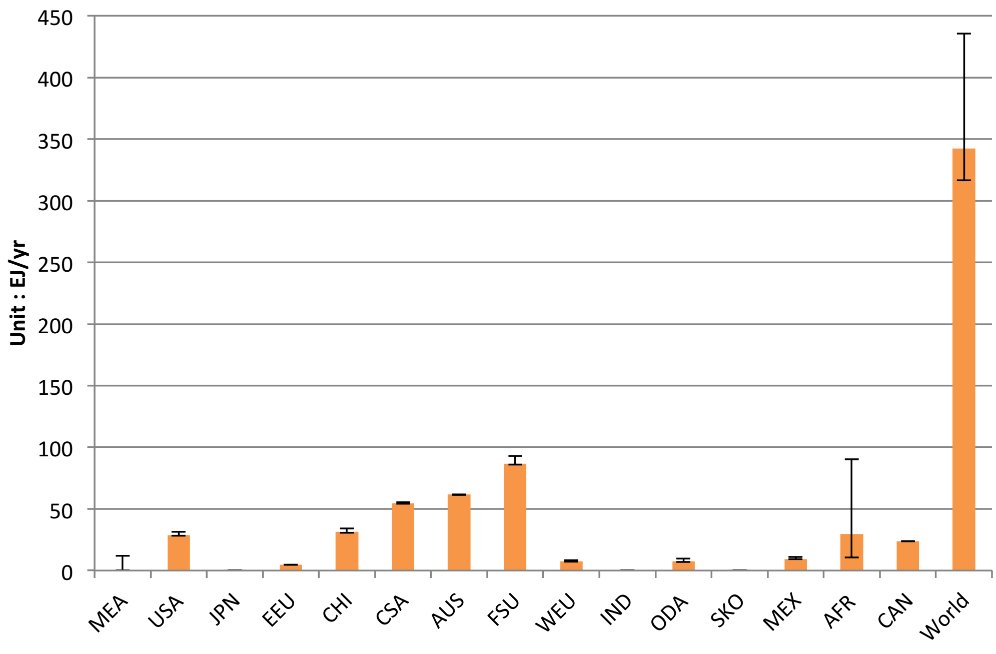


Figure 8. Agricultural bioenergy potential by 2050

As shown in table 10, bioenergy potential from M.Hoogwijk, 2005 achieved about 657EJ/yr under A1 scenario while our study estimated it in the range from 316-435EJ/yr. However, energy crops productivity applied in M.hoogwijk,2005 study (10-20MJ/kg for surplus agricultural land and 1-10MJ/kg for degraded land) is higher than our estimation (a constant average of 7.5MJ/kg). Furthermore, considering that our bioenergy potential will be directly introduced in surface data with region and crop specific productivity projections, final bioenergy potential could be similar to the results of M.Hoogwijk.

Study	Type of potential	Regions	Time frame	Land use types	Potential
WBGU, 2008	Technical	Global	2050	Land suitable for bioenergy cultivation according to the crop functional types in the model, considering sustainability	34-120EJ/yr
Smeets et al, 2007	Technical	Global	2050	Surplus agricultural land (100%)	215 – 1272 EJ/yr
Hoggwijk et al.,2003	Technical	Global	2050	Surplus agricultural land, Surplus degraded land	8 – 1098EJ/yr
Hoggwijk et al.,2005 [29]	Technical	Global	2050-2100	Abandoned agricultural land (100%), Remaining land not for food or material production (10-50%), Extensive grassland	Total : 311-657 EJ/yr(Climate scenario A1 : 657EJ/yr)
Erb et al., 2009	Technical	Global	2050	Cropland not needed for food and fiber supply intensification of grazing land	28-128EJ/yr
Our study	**Technical**	**Global**	**2030-2050**	**Surplus agricultural land (100 %), Grass and other wooded land (limited to soil quality)**	**316-435EJ/yr**

Table10. Overview of litterature review on bioenergy potential from energy crops. (adopted from IIASA [26], modified by author)

In the case of agricultural residues, energy potential from this source is estimated based on future food demands. Hence, total crops production and available residues may change by the type of animal production system, for example, landless animal production requires more feed crops by replacing pasture and grasses with feed and fodder crops. Furthermore, different limits of recoverability fraction may result differences in bioenergy potential from agricultural residues. As the projection on food demands remains constant regardless of crops yields and animal grazing system, two levels of recoverability fraction and two animal production systems derived four scenarios to estimate bioenergy potential from agricultural residues as described in table 11.

No.	RF limit	Animal production system	Results
Scen1	0.5	Landless	111EJ/yr
Scen2	0.5	Mixed	79EJ/yr
Scen3	0.25	Landless	55EJ/yr
Scen4	0.25	Mixed	39EJ/yr

Table 11. Agricultural residue scenarios and results

As results, world bioenergy potential from agricultural residues is estimated in the range from 39 EJ/yr (Scen4) to 111 EJ/yr (Scen1). These results may be compared with 49-69EJ/yr by Smeets et al.[5], 50EJ/yr (technical) by IIASA [21] and 10-32EJ/yr by M.Hoogwijk [23]. Differences in bioenergy potentials from agricultural residues mainly come from different assumptions on residue to product ratio (RPR) and recovery fraction (RF). For example, the agricultural residues estimated by M.Hoogwijk applied 25% usability fraction of the total available agricultural residues as well as Smeets et al. Among our scenarios, scen3 and scen4 applied 25% of usability ratio, then, agricultural results are estimated between 39EJ/yr and 55EJ/yr, which are not dissimilar with those estimations.

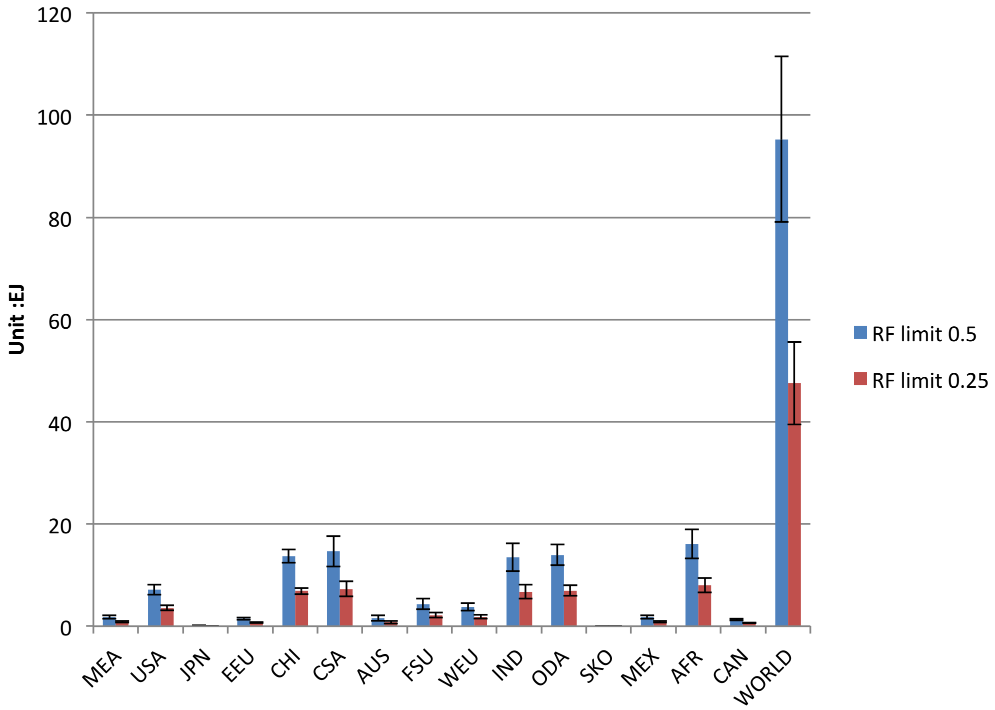


Figure 9. Bioenergy potential from agricultural residues by 2050

3- Bioenergy from forestry

Historically, forestry biomass has been widely used in the world. The consumption of forestry biomass consists of two types, firstly, traditional use for cooking and heating, secondly, modern use for transformation into biofuels and compacted woody biomass by increasing energy contents. However, wood logging from forest may derive a serious deforestation and corresponding climate change from reducing carbon stock capacity of forest. Hence, in this chapter, we tried to verify the maximum forestry bioenergy potential without degrading the environment.

3-1- Methodology

In this study, total woody biomass potential is limited to the sustainable surplus forest supply, for which supply side and demand side were separately estimated. In the case of supply side, 3 different types of supply; wood supply from (1) forest, (2) other wooded land, and (3) trees outside forest, are included in our calculation. In demand side, industrial roundwood consumption is estimated. The total surplus forest supply estimation can be expressed as equation xxx.

Surplus wood supply

= Supply from forest + supply from other wooded land + supply from TOF - industrial roundwood demand

Lastly, forestry biomass potential becomes the sum of surplus wood supply, logging residues, processing residues, and wood products residues.
The following sections describe the methodology applied for different types of woody biomass as well as demand projection.

3-1-1- Woody biomass from forest and other wooded land

To estimate sustainable potential of woody biomass, GAI (Gross Annual Increment) is estimated for each region. FAO defines GAI as "Average annual volume of increment over the reference period of all trees, measured to a minimum diameter breast height (d.b.h.) of 0 centimetres (cm) including the increment on trees which have been felled or die during the reference period". Hence, this indicator allows estimating annual natural forest growth and limiting exploitation of woody biomass not more than natural growth level. Currently, FAO includes only NAI (Net annual increment), which excludes felled amount of trees from GAI, in forest resource assessment. Furthermore, FAO does not provide NAI for different categories of wood land type (forest, other wooded land, and TOF). Therefore, GAI for each region and each type of wood land needs to be re-estimated using growing stock, forest surface, wood removal, and dead wood stock data. GAI and NAI estimations followed the next equations [30] .

$$GAI_{land,region} = \frac{\left((GS_{land,region,time} - GS_{land,region,0}\right) + \left(F_{land,region,time} - F_{land,region,0}\right) + \left(NL_{land,region,time} - NL_{land,re}\right.}{Time - 0}$$

Where:

$GS_{land,region,time}$ = Total growing stock at time in land type and region

$GS_{land,region,0}$ = Initial growing stock in land type and region

$F_{land,region,time}$ = Felling trees at time in land type and region

$F_{land,region,0}$ = Initial volume of felled trees in land type and region

$NL_{land,region,time}$ =Volume of trees died naturally at the time in land type and region

$NL_{land,region,time}$ =Initial volume of naturally died trees at the time in land type and region

$$NAI_{land,region} = GAI_{land,region} - NL_{land,region}$$

In the case of the Natural losses, none of statistics provides proper information at global coverage. Instead, deadwood stocks for each region and landtype are available to replace natural losses data, which can be considered as mortality (death of trees through natural tree death, insect attacks, fire, wind-through or other physical damage). This assumption, made in our study, has been also used in other literature to derive GAI of forests [31].
Moreover, total wood removals needs to be separately calculated for each land type, while FAO's data on wood removals are not distinguished according to land types. Hence, a methodology to allocate wood removals to different land types, which are "Forest" and "Other wooded land" is developed. In details, FAO defines that forest is a 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, and that other wooded land is Land not defined as "Forest", spanning more than 0.5 hectares; with trees higher than 5 meters and a canopy cover of 5-10 percent, or trees able to reach these thresholds; or with a combined cover of shrubs, bushes and trees above 10 percent. Also, other wooded land can include areas of shrubs and bushes where no trees are present. Hence, In this methodology, we assumed that the industrial roundwood comes mostly from forest rather than from other wooded land based on wood/forest characteristics. On the other hand, fuelwoods can be exploited from both "forest" and "other wooded land", then, fuelwood removal is allocated to each land type based on the proportion of surfaces.
In addition, to distinguish economic potential and technical potential, the share of commercial species of total growing stock is applied during GAI calculation.

Region / Subregion	Commercial species (% of total growing stock)			
	1990	2000	2005	2010
Eastern and Southern Africa	16.2	16.4	16.4	16.5
Northern Africa	75.6	73.3	72.6	71.8
Western and Central Africa	20.7	21.0	21.3	21.6
Total Africa	**19.7**	**20.0**	**20.2**	**20.5**
East Asia	67.0	45.7	32.3	32.4
South and Southeast Asia	29.2	29.1	28.8	28.8
Western and Central Asia	66.6	64.9	58.9	53.8
Total Asia	**52.8**	**41.5**	**33.2**	**32.9**
Europe excl. Russian Federation	99.4	99.4	99.5	99.5
Total Europe	**99.9**	**99.9**	**99.9**	**99.9**
Caribbean	65.3	73.9	77.0	78.0
Central America	17.1	17.1	17.1	17.1
North America	89.8	91.6	91.6	91.5
Total North and Central America	**87.1**	**89.3**	**89.6**	**89.8**
Total Oceania	**51.2**	**51.2**	**51.2**	**51.2**
Total South America	**35.8**	**35.8**	**35.8**	**36.0**
World	**60.0**	**60.7**	**60.7**	**61.6**

Table 12. Share of commercial species from FRA2010 [27]

The calculated GAI (unit : m3/ha) either commercial and technical is multiplied by each surface to estimate total woody biomass supply in volume.
Then, Surplus wood supply is combined with region-specific BCEF (Biomass conversion and expansion factor) for growing stock, which is published by IPCC and FRA 2010 report. BCEF allows converting wood volumes to above ground biomass in dry matter basis weights.

Region / Subregion

Region / Subregion	Biomass conversion and expansion factor	Root-Shoot ratio	Dead-live ratio
Eastern and Southern Africa	1.94	0.26	0.21
Northern Africa	2.15	0.28	0.29
Western and Central Africa	1.07	0.23	0.09
Total Africa	**1.24**	**0.24**	**0.13**
East Asia	0.66	0.31	0.14
South and Southeast Asia	1.43	0.30	0.11
Western and Central Asia	0.82	0.28	0.02
Total Asia	**1.08**	**0.30**	**0.12**
Europe excl. Russian Federation	0.67	0.26	0.06
Total Europe	**0.65**	**0.25**	**0.17**
Caribbean	1.51	0.24	0.11
Central America	1.04	0.24	0.11
North America	0.76	0.22	0.11
Total North and Central America	**0.78**	**0.22**	**0.11**
Total Oceania	**0.77**	**0.33**	**0.18**
Total South America	**0.99**	**0.20**	**0.06**
World	**0.92**	**0.24**	**0.11**

Table 13. Biomass conversion and expansion factor from FRA2010 [32]

3-1-2- TOF (Trees outside forests)

Apart from woody biomass from forest and other wooded land, TOF is an important source of woody biomass supply, while the assessment on TOF still suffers from insufficient data, and only few countries are providing corresponding information. Recently, FAO recommends the country members to include TOF information in FRA2015[33] country reporting and also realized a study on TOF assessment [34]. In FRA 2015, a part of TOF potential is assessed for some countries regarding to “other land with trees cover”. However, the number of countries that reported TOF information remains still insufficient According to FAO’s definition on “other land with trees cover”, wood supply from TOF in the range of 5 and 10% of canopy cover is excluded as well as trees on other wooded land.
Figures 10 and 11 show different decision trees of other land with tree cover and other land with TOF. In the decision tree for other land with TOF, wood supply from OLwTOF (NON A/U -2) and OLwTOF (NON A/U -1) are not included in other land with trees cover, but allocated in other land without tree cover or other wooded land.

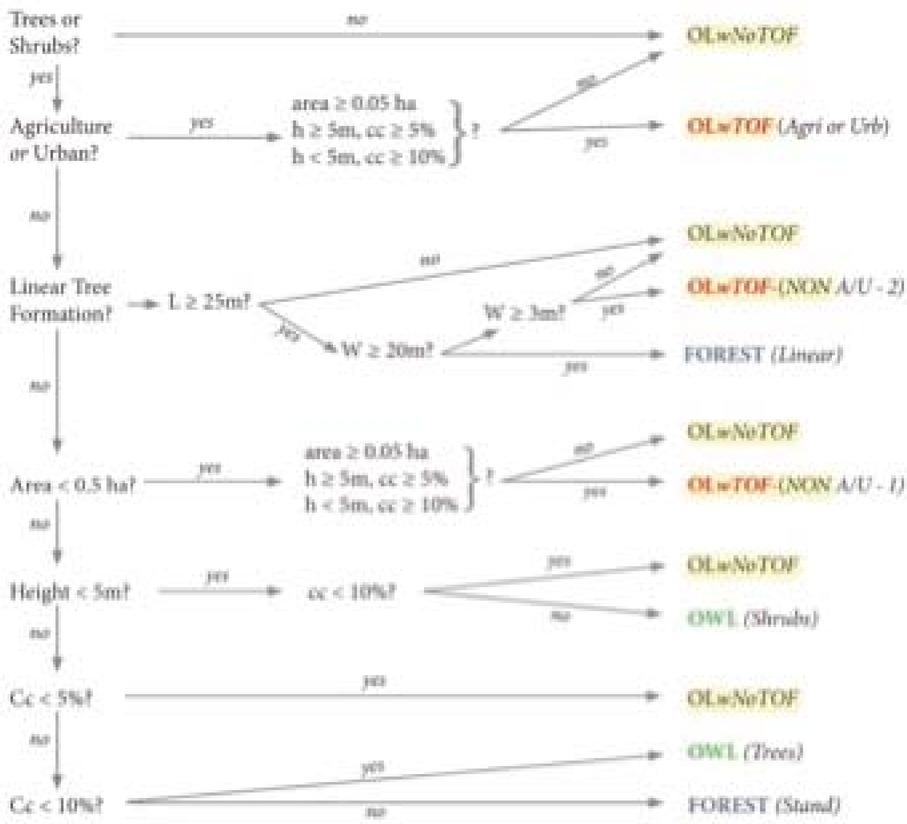


Figure 10. Decision tree for other land with TOF (cited from FAO)

They visualize the threshold of each forestry land type and its classification. Based on these figures, we can identify that other land with tree cover is fully embedded in other land with TOF.

In addition to data on TOF from "FRA 2015" and "Towards the Assessment of Trees outside Forest", literature review was addressed to complete the dataset. For example, TOF information of China is not available in both of those two major sources even though the large potential of TOF. Chinese government defined TOF as four side trees, which refers to trees growing and distributed along the sides of the houses, roads, rivers, and cropland. Then, the corresponding data is directly extracted from the national forest inventory of China [35].

To finalize the estimation of wood supply from TOF, surface data needs to be combined with wood production yields. FAO's definition on TOF proves that land and woods classification criteria for land with tree cover matches to the characteristics of forest land (see figure 12).

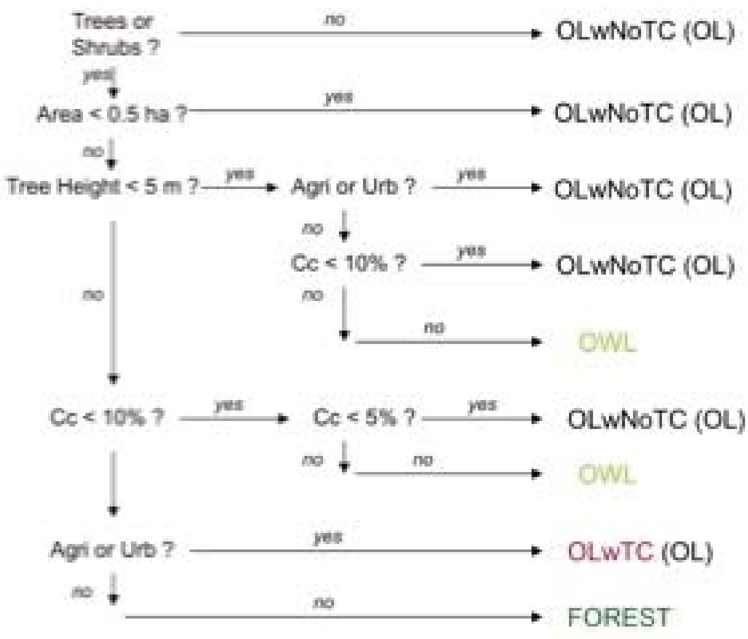


Figure 11. Decision tree for other land with tree cover (cited from FAO)

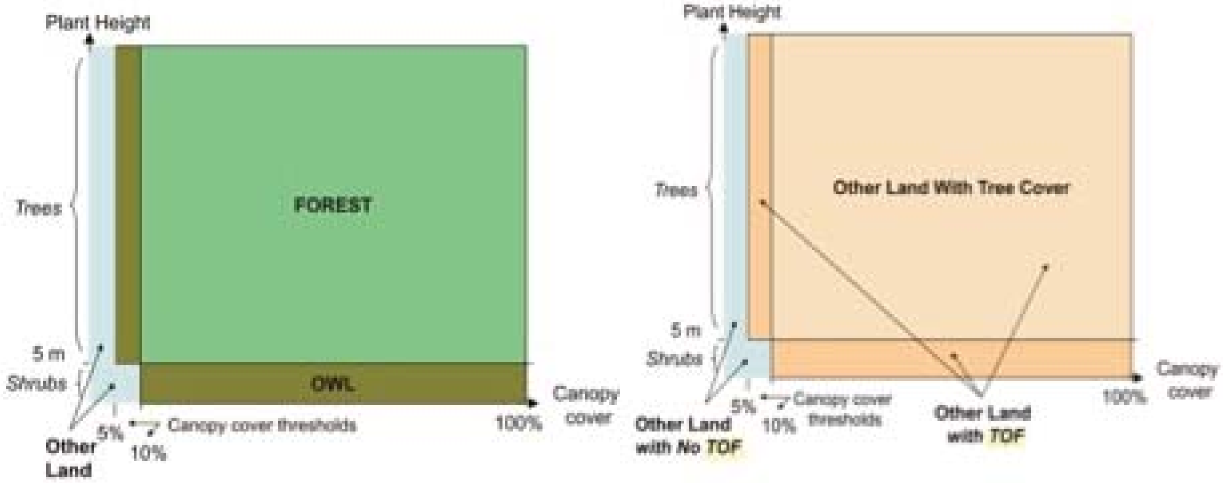


Figure 12. TOF classification (cited from FAO)

Hence, region-specific GAI data on forest land are used to derive woody biomass potential on land with tree cover and to conserver sustainable level of wood exploitation. According to a study of S.Schelle et al [36], wood productivity on other land with TOF is identified as similar with growth rate in other wooded land. Also, the tree classification thresholds states that land and tree characteristics correspond to trees on other wooded land. Currently, other land with TOF data is not available for all countries. Only for the countries where TOF data is available, the remaining surface after extracting the surface of land with tree cover is multiplied with region specific GAI data on other wooded land to estimate woody biomass potential (see equation on TOF).

$$TOF_{region,year} = OLwTC_{region,year} \times GAI\ forest_{region,year} + (OLwTOF_{region,year} - OLwTC_{region,year}) \times GAI\ other_{region,year}$$

Where :

$OLwTC_{region,year}$ = Surface of other land with tree cover in region and year

$OLwTOF_{region,year}$= surface of other land with TOF in region and year

3-1-3- Wood residues

Wood residues are composed of 3 elements as logging residues (harvest residues), processing residues, and wood wastes. To estimate these 3 wood residues, residues estimation methodology of E.M.W. Smeets [37] are applied. Firstly, for logging residues, wood removals data is combined with logging residues generation ratio and recoverability ratio. Due to the lack of regional specific data, global average ratios are widely adopted. Secondly, processing residues are assumed to be produced only with industrial roundwood consumptions because of the difficulty to distinguish industrial fuelwood productions with direct use of fuelwood. Similarly, wood wastes from discarded wood products ad tertiary residues were assessed using wood product generation ratio and wood wastes residue recoverability fraction. The detailed methodology is expressed as follows.

- Logging residues
    - LR = PI x h x hr x D x HV [EJ/year]

      - LR : Logging residues
      - PI : Industrial roundwood production
      - h : Logging residue generation ratio (set at 0.6 , lack of regional specific data)
      - hr : Logging residue recoverability
      - D : dry matter conversion rate (0.56 tDM / m3, IPCC default value)
      - HV : Heating value (20GJ/tDM)

- Processing residues
    - PR = CI x p x pr x D x HV [EJ/year]

      - PR : Processing residues
      - CI : Industrial roundwood consumption
      - P : processing residue generation ratio (set at 0.5)
      - Pr : processing residue recoverability ratio (set at 0.75)
      - D, HV : same as logging residues

- Wood wastes
    - DW = CI x w x wr x D x HV [EJ/yerar]

      - CI : Industrial roundwood consumption
      - W: wood product generation ratio (set at 0.5)
      - Wr : Wood waste recoverability ratio (set at 0.75)
      - D, HV : same as logging residues

3-1-4- Wood demand projection

In this study, fuelwood consumption is considered as one of the bioenergy sources unlike to other literatures. The choice of fuelwood remains to the optimization results via the energy system model TIAM-FR. Hence, wood demands are projected only for industrial round wood. Currently, wood demand projection is hardly available for region-specific data and if available, region definition differs from TIAM-FR. According to literature review, the world total demand of industrial roundwood is projected to normally be in the range from 0.9Gm3 (10 EJ) to 3.1 Gm3 (36EJ)(3) [37–39] and is not dissimilar with simple projection using current consumption per capita level. Thus, Industrial roundwood demands are estimated based on constant region specific ratio of consumption per capita and demographic evolution from UN. As results, Industrial roundwood demand in world is estimated to about 23 EJ by 2050, and it remains on the level of projection from other studies.

(3)In extreme case, industrial roundwood demand reaches to 80EJ by 2050 (Sedjo and Lyon, 1998 [42])

3-2- Results: Forestry biomass

Forestry biomass potential is estimated from different wood supply sources as surplus forest growth, wood from TOF (Trees Outside Forest), and forestry residues based on the methodology mentioned in previous sections. It should be noted that fuelwood consumption is excluded from wood demand prospective and considered as a source of bioenergy, then, included in final forestry bioenergy potential. In the case of wood supply potential, two different scenarios are developed, which are technical potential on the one hand, and economic potential on the other hand. The difference in those two scenarios comes from different GAI indices. In details, GAI results are applied in order to derive technical potential of wood supply and GAI results combined with commercial growing stock rate in total growing stock are applied for economic potential.

First of all, sustainable wood growth is calculated as the range of 101.85EJ/yr for technical potential and 55.45EJ/yr for economic potential (see table xxx). The difference between two scenarios comes from different commercial species share in total wood species and following GAI data. Under technical potential estimation, global average GAI data are estimated to 2.91 m3 /ha/yr for “forest” and 1.98 m3/ha/yr for “other wooded land”. However, these estimations decreased with excluding non-commercial volumes to 1.91 m3/ha/yr for “forest” and 1.12 m3/ha/yr for “other wooded land”. Our estimation on sustainable wood growth is in the line with wood supply potential from forest of 103EJ (with global GAI of 3.4 m3/ha/yr) for technical potential and 45 EJ/yr (with global GAI of 2.1m3/ha/yr) for economic potential estimated by E.M.W. Smeets [37].

UNIT: EJ		Sustainable wood growth			
Country	Technical	Economic	**Country**	Technical	Economic
MEA	0.70	0.37	**WEU**	7.05	7.02
USA	12.37	11.16	**IND**	14.99	4.32
JPN	1.68	0.56	**ODA**	5.26	1.56
EEU	4.23	4.20	**SKO**	0.52	0.17
CHI	4.75	1.60	**MEX**	0.13	0.10
CSA	11.08	2.76	**AFR**	20.94	5.54
AUS	2.30	1.18	**FSU**	7.94	7.86
CAN	7.93	7.05	**World**	**101.85**	**55.45**

Table 14. Sustainable wood growth by 2050

Including wood supply from TOF, forestry residues and wastes, final forestry biomass potential by 2050 is derived as 114EJ/yr for technical potential and 68EJ for economic potential, of which residues and wastes contribute 18.4 EJ/yr. The forestry residue estimation is in the line with other studies, 19-35EJ/yr by IIASA [21] and 28 EJ/yr by Smeets[37]. However, it should be noted that fuelwood demand is included in these estimations under assumption that it would be an internal choice of optimization results from TIAM-FR. On the other hand, applying fuelwood demands projected by M.W.Smeets in the range of 20EJ – 30EJ, our final estimation becomes 84EJ – 94 EJ for technical potential and 38EJ/yr – 48 EJ/yr for economic potentail. These results may be compared with other studies, for example, 90-115EJ of technical potential estimated by Fischer [40], 91.9 EJ/yr of technical potential and 42.5EJ/yr of economic potential estimated by E.M.W. Smeets and 12-74EJ by IPCC AR4 [41].

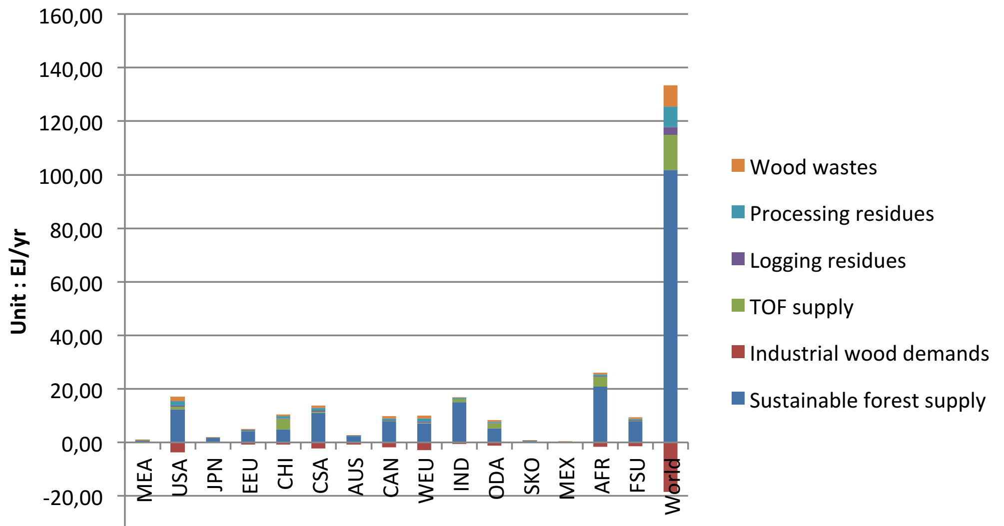


Figure 13. Total forestry bioenergy potential by 2050 (technical potential)

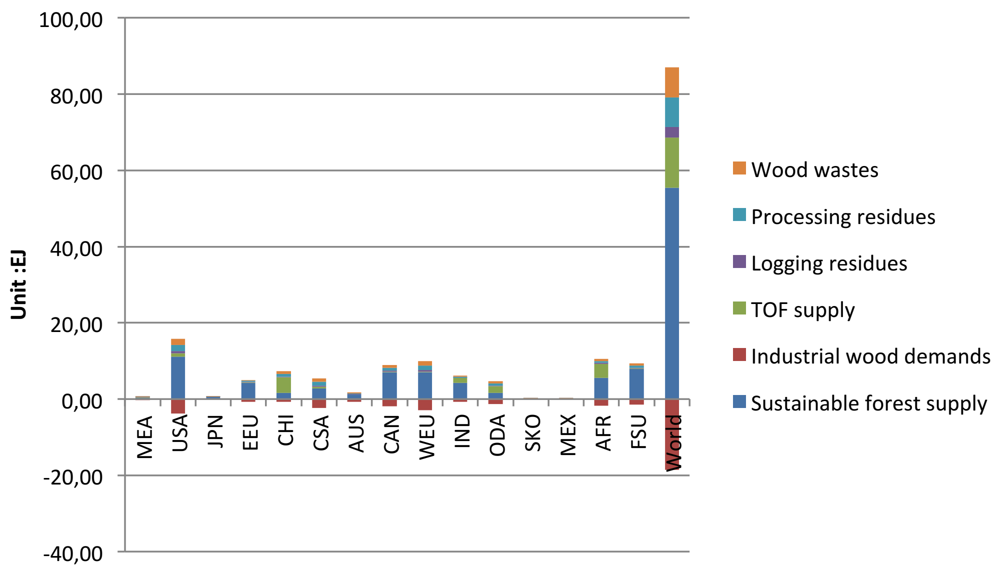


Figure 14. Total forestry bioenergy potential by 2050 (economic potential)

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Working Paper N°2016-03-21