The assessment of biofuel potentials on global and regional scales in the tropical world

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This paper deals with the evaluation of biofuel potentials through the spatial analysis of the conditions for the emergence of biofuels. A method for the assessment of potential land availability in developing countries is presented. It allows for the identification of countries with the highest long-term (2050) potentials for dedicated biomass energy plantations, considering that food and feed requirements are given priority. This approach helps illuminate future agricultural yields and practices that will be required to simultaneously meet food, feed, and biofuel objectives. The paper then discusses three issues impacting the results: biofuel conversion technology, biomass logistical aspects and the availability of agri-based residues (primary and secondary).

1. Introduction

The contribution of biomass to the global energy supply has been widely studied and modelled for prospective purposes. Estimates differ widely, from 33 to 1135 EJ per year in 2050 [Hoogwijk et al., 2003]. The estimated potentials are unevenly spread out geographically:

- low potential in North Africa and South Asia: these regions resort to agricultural imports;
- moderate potential in South-east Asia, due to the use of degraded soils; and
- high potential in other areas:
  - the Caribbean, Latin America, Sub-Saharan Africa: surplus production capacity related to the existence of large rangelands that could be better managed;
  - ex-Soviet and Baltic countries: following the decline of the communist system, agricultural consumption, production and output decreased, and the population is decreasing;
  - Oceania: potential for output growth and reduction of arable lands; and
  - North America: significant potential from treatment of crop residues, in addition to that from former cropland.

These general results show that the places with the most promising potential for bioenergy do not coincide with the places where the highest energy demand is expected. This discrepancy is one reason for focusing on bioenergy that can be produced on large scales and then exported, such as biofuels from plantations [Dameron et al., 2005][1].

Several estimates of the biofuel potential are based on FAO data (land area, world production for agriculture, forestry, etc.) at the regional or country level, but generally provide little additional geographical information about where precisely the areas of interest for the biofuel plantations and other bioenergy sources lie. Yet such information is necessary for the further validation of the preliminary estimates and for conducting a sensitivity analysis with respect to key assumptions.

The estimation of the bioenergy potential mainly depends on an assessment of land availability, yield levels for biomass production and transformation, and on the competition among alternative land uses and among the various alternative biomass conversion processes. Such estimations are useful on a country basis because decisions about entering into bioenergy development need to be taken or at least assented to at the national level, taking into consideration other national priorities[2].

This paper focuses on biofuels from plantations in the tropical world but also considers agricultural and forestry residues. The purpose of this paper is to put forward a methodology applicable to tropical regions as well as East Asia, the Pacific and non-tropical South America, designating the countries where the bioenergy potentials from plantations may deserve specific attention. We start with

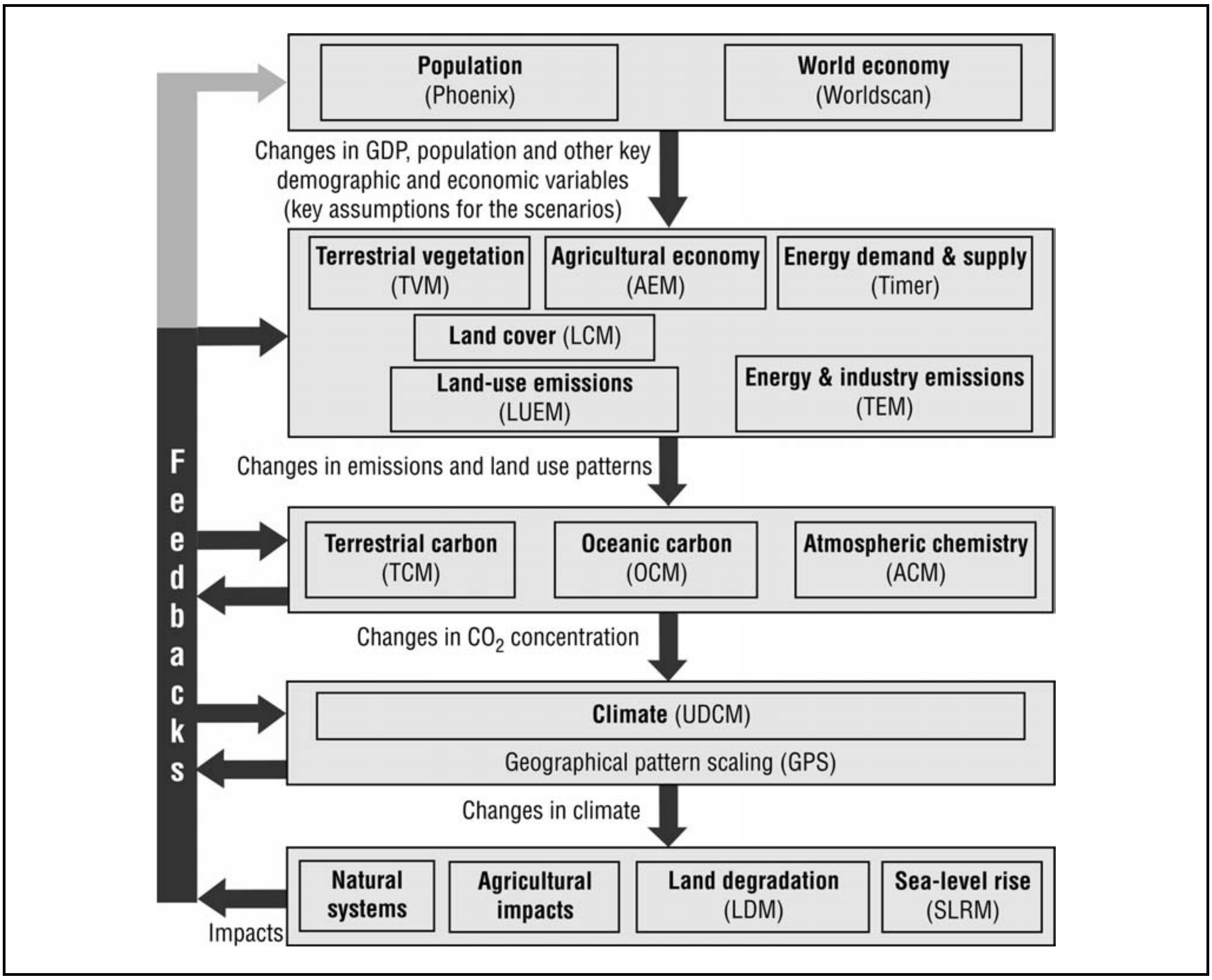

Figure 1. Structure of IMAGE [Alcamo et al., 1998]

a global assessment of biomass resources and progressively narrow the field down to more local scales.

2. Studying land availability for energy plantations

Following a presentation of the methodologies, we provide some initial estimates of global potential for energy plantations, based on our on-going studies at the Center of International Cooperation in Agricultural Research for Development (CIRAD). The methodologies deal with the issue of food versus energy competition for land use but *not* with the related issue of competition between biofuels and other non-food crops or plantations. The methodologies will allow us to identify the main parameters affecting the estimations and the need for further assessment.

We have combined an estimation based on land cover scenarios and a feedback study on how an estimation of the potential translates to assumptions about the evolution of agriculture: area cultivated and agricultural yields.

2.1. The assessment of potential land availability starting with land cover scenarios to 2050

2.1.1. Resorting to global earth observation data and IMAGE projections

The initial assessment of potential land availability for energy plantations is based on data and results from the global integrated assessment model, IMAGE [IMAGE, 2001], implementing SRES (Special Report on Emission Scenarios [IPCC, 2000]) scenarios A2 and B1. Development in the A2 scenario is of a more material/economic and regional nature, while in the B1 scenario, it is of a more social/environmental and global nature.

IMAGE is an integrated assessment model for climate change issues that provides an interdisciplinary and geographic overview of the society-biosphere-climate interactions based on assumptions about the evolution of agricultural yields and other parameters. As shown in Figure 1, the demographic and economic assumptions resulting from other long-term models feed three sub-systems: (1) the Energy-Industry sub-system, determining energy consumption and emissions; (2) the Terrestrial Environment sub-system concerning land use; and (3) the Atmosphere-Ocean system, concerning changes in climatic properties.

IMAGE starts from an initial situation (1970) and observed data until 1995. Its scenarios of evolution to 2100 are mainly based on a calibration of observed data and assumptions about the future, with some gradual readjustments.

The Land Cover Model and the Terrestrial Vegetation Model are two components of the Terrestrial Environment sub-system. At any time, depending on the climatic and soil conditions, the potential natural vegetation is determined for each 0.5º × 0.5º grid cell of the world. For each 5-year step, given the regional demand for food, feed, biofuel crops and timber products, timber extraction and agricultural needs are computed (including grass and fodder needs).

The original global earth-observation data on which the model is calibrated is the Global Land Cover Characteristics Database (GLCCD) based on the large-scale sensor AVHRR (Advanced Very High Resolution Radiometer). Such global earth mapping consists in allotting to the whole land cover an identification class compared to the characteristics of the place "more or less natural or anthropic". Before obtaining a map, initial data go through several stages of processing and are divided into named classes. Filters are then used to produce a final map that can be interpreted by the end-user.

The major problem for the quality of such maps lies in the choice of the nomenclature adopted and a regular updating of the data. Vegetation and land cover can change rapidly (10 % per decade on average), with strong seasonal and inter-annual variations, requiring the constant use of improved data (more recent, better validated). The ultimate accuracy of the map often depends on the final user needs.

No thematic map currently exists at the global level for potentially available surfaces for energy plantations to produce biofuels. So, unless a new mapping exercise is undertaken (our first results on this are expected in mid-2006), the estimation of land potentially available for energy derives from the interpretation of existing maps after the relevant land cover categories have been identified.

Our study on land availability for biofuel production based on IMAGE scenarios is based on the following nomenclature and assumptions.

Forest areas are not considered available for biofuel plantations. "No deforestation" is a basic ethical rule implying that no forest should be transformed into plantations. However, forestry residues will be considered among other residues as possible feedstock for biofuels (see Section 3.3).

Degraded forests usually range from sparse remaining trees on an open surface, with little or no hope for natural replenishment, to open forests with significant tree cover, which can naturally return to a closed forest state. A fine local approach is required to take into account ecological and social aspects and distinguish: (1) natural regeneration; (2) a mixture of natural replenishment with energy crops or plantations; and (3) fast-growing plantations over the entire zone.

Agricultural lands are lands cropped or grazed intensively, plus fallows. Since they are used for agriculture and food end-use, we will not consider them as available for additional biofuel production[3]. The question of agricultural residues is sensitive and discussed in Section 3.3.

However, when, as a result of the evolution of agricultural productivity for instance, agricultural lands are abandoned, they are supposed to: (1) revert more or less rapidly to a natural biome; and (2) be potentially available for biofuel crops. Abandoned agricultural land should derive from lost fertility or food satisfaction due to improved productivities. The corresponding areas are computed in the IMAGE model according to its assumptions about the yield evolutions in the various parts of the world.

Extensive grasslands are lands covered by grass with a low productivity potential, often grazed extensively. Although naturally poor, they can be suitable for biofuel plantations (such as the littoral savannas of Gabon or the Republic of Congo (i.e., Congo (Brazzaville), or the Bateke highlands).

The *savannas* cover various lands ranging from a few trees on a herbaceous and shrub layer to more significant tree cover on grass and shrubs. The *scrublands* represent more wooded lands than savannas. The savannas and the scrublands represent biomes on a natural path to afforestation and generally biomes that are ecologically interesting to keep undisturbed (from the viewpoint of biodiversity).

2.1.2. Assessing global land potential in tropical regions (plus East Asia, the Pacific and non-tropical South America)

A step-by-step method is used for assessing potential land availability for bioenergy plantations, considering that competition between food and energy should be avoided as much as possible.

- Countries with potential for bioenergy production are selected through the application of predefined criteria at the grid cell level (0.5º × 0.5º) on at least one-third of the national territory in 2000: minimum rainfall level of 800 or 1000 mm/year, maximum population density of 80/km^2.
- The available land areas in these countries are evaluated using another set of criteria considering each selected country's situation, mainly geopolitical, considering neighbouring countries.
- IMAGE and GLC2000 projections are used to assess how these lands may evolve by 2050.

By applying rainfall and population density selection criteria, we do not imply that it is impossible to grow biomass for energy elsewhere, but we do not include these areas in the assessment of potentials at this stage where the study is still global.

The aggregated results by region according to the IMAGE scenarios are given in Table 1.

For 2000, for the two levels of minimum rainfall, 800 and 1000 mm per year, land potentials are estimated to be 335 and 407 Mha (million hectares) respectively.

By 2050, the interval widens considerably, covering values for the two scenarios and the two rainfall thresholds, ranging from 175 to 583 Mha.

Whatever the scenario and the rainfall threshold, South America and Africa should offer the largest potentials.

The land assessment process we described leads to the identification of countries where more detailed studies are to be conducted (Table 2). Strictly applying the aforementioned criteria, twenty-two[4] countries were selected with widely differing characteristics, for example Brazil and

Table 1. Aggregated results obtained for various regions, scenarios, and time horizons, in Mha

Minimum rainfall: 800 mm		2000	2030 B1		2030 A2		2050 B1		2050 A2	
Selected countries	**Total area**	**Potentially available area**	**Potentially available area**	**including abandoned agr. land**	**Potentially available area**	**including abandoned agr. land**	**Potentially available area**	**including abandoned agr. land**	**Potentially available area**	**including abandoned agr. land**
in Africa	927	185	124	126	87	87	148	204	76	76
in South America	1573	142	161	256	113	114	134	249	85	86
in Asia (incl. West Asia)	1537	32	23	29	23	23	18	33	15	16
in Pacific	804	48	54	87	53	71	54	96	53	75
Total selected countries	4841	407	361	498	275	296	355	583	230	254
Total incl. non-selected countries	5044	417	559	315	336	40	418	674	262	289
Minimum rainfall: 1000 mm		**2000**	**2030 B1**		**2030 A2**		**2050 B1**		**2050 A2**	
Selected countries	**Total area**	**Potentially available area**	**Potentially available area**	**including abandoned agr. land**	**Potentially available area**	**including abandoned agr. land**	**Potentially available area**	**including abandoned agr. land**	**Potentially available area**	**including abandoned agr. land**
in Africa	927	158	104	107	71	71	124	174	61	61
in South America	1501	122	132	214	96	97	108	207	73	73
in Asia (incl. West Asia)	1537	27	16	18	16	16	13	19	10	10
in Pacific	804	29	33	53	32	43	33	60	32	46
Total selected countries	4768	335	286	391	216	228	278	459	175	190
Total incl. non selected countries	5116	58	321	433	241	252	312	510	195	211

the Central African Republic. In addition to these 22 countries, we take into consideration four countries because their potentially available areas are significant even through they do not represent more than one-third of the country's area: China, Australia, Argentina and Chile.

It can be noted that no industrialized countries except Australia and New Zealand are on the list. This is essentially due to population density criteria (at least one-third of the country area having population density less than 80/km^2 in 2000).

These results derive from the IMAGE model with its specificities and from the constraints we thought would best address the issue of potential land availability within a global study. Such systematic treatment does not prevent the exclusion of interesting zones (e.g., industrialized countries where the selection criteria could be less strict because of high technology level) and on the other hand the inclusion of zones where energy crops would be highly improbable (e.g., land-locked areas with very low population density). Imperfections may come from land nomenclature (definition of forests for instance) or additional constraints that should be taken into account (altitude, soil type, etc.).

2.1.3. Revising the initial estimates with country-specific or more local studies: the case of Brazil [Wichert, 2005]

The first step consists in using 2050 scenarios, counting the number of yellow and red pixels[5] by region and biome, corresponding to B1 and A2 SRES scenarios. For Brazil, this counting indicated that out of 111 Mha potentially available today, for the A2 scenario (more pessimistic in terms of accounting for the global environment, red pixels in the original version of the map in the top left-hand corner; these are the darkest grey in the version printed here) only 31 % will be retained in 2050, whereas for the B1 scenario (more optimistic, yellow pixels in the original map; these are the lightest grey in the version printed here) 69 % of the area potentially available today will be retained in 2050.

The second step consists of verifying the relationship between the IMAGE indicator map and national maps providing further information about protected areas (reserved for the Indian (i.e., indigenous) population and for national and state parks), population density and rainfall data (Figure 2). The protected areas are various shades of grey in the map in the bottom left-hand corner.

The overlapping areas were excluded from the initial 111 Mha estimate of potentially available land for energy plantations in Brazil, representing a decrease of 33 % to 77 Mha.

The main factors influencing this reduction in area were the overlapping of areas on the IMAGE 2.2 map with those containing Indian reservation areas, federal and state conservation units, and areas with population densities above 80/km^2, especially along the North-Eastern coast.

2.1.4. Need for feedback about global assessment

The same approach could be adopted for further country-specific studies so as to revise the initial assessments about current potential land availability and subsequent assessments based on the land cover projections. Clearly, biomass production for energy will compete with food

Table 2. Result by country with the 800 mm/yr minimum rainfall criteria, in Mha

800 mm threshold	Areas considered in % of the total area of the country		2000	2030 B1		2030 A2		2050 B1		2050 A2	
Country	Rainfall criteria 800mm	Population criteria 2050–A2 proj	Potentially available area	Potent. available area	including aband. agr. land	Potent. available area	including aband. agr. land	Potent. available area	including aband. agr. land	Potent. availa-ble area	inclu-ding aband. agr. land
Angola	72 %	68 %	35	25	27	9	9	29	41	9	9
Congo, Democratic Republic	100 %	85 %	26	15	15	13	13	18	30	9	9
Central African Republic	99 %	98 %	24	22	22	20	20	21	22	18	18
Zambia	85 %	79 %	23	15	15	11	11	25	36	11	11
Mozambique	81 %	56 %	19	10	10	6	6	14	19	6	6
Tanzania	84 %	58 %	17	7	7	3	3	7	8	3	3
Guinea	100 %	77 %	9	7	7	6	6	8	10	4	4
Madagascar	89 %	73 %	7	6	6	3	3	9	14	3	3
Cameroon	95 %	70 %	6	4	4	3	3	3	4	2	2
Côte d'Ivoire (Ivory Coast)	100 %	55 %	6	3	3	3	3	3	3	2	2
Congo (Brazzaville)	100 %	98 %	4	4	4	4	4	4	9	4	4
Benin	98 %	66 %	4	3	3	2	2	3	3	2	2
Ghana	100 %	37 %	2	2	2	1	1	2	2	1	1
Guinea-Bissau	100 %	41 %	2	2	2	1	1	1	1	1	1
Gabon	100 %	97 %	1	1	1	1	1	1	3	1	1
Brazil	95 %	83 %	111	129	197	95	95	108	186	74	74
Bolivia	65 %	65 %	10	8	13	6	6	4	13	2	2
Venezuela	96 %	76 %	8	12	17	4	4	11	17	3	3
Argentina	30 %	22 %	4	3	9	1	2	3	9	1	2
Paraguay	82 %	74 %	3	2	3	2	2	3	4	2	2
Chile	23 %	21 %	2	2	4	2	2	2	4	2	2
Colombia	95 %	66 %	2	2	10	1	1	2	14	1	1
Ecuador	88 %	61 %	1	1	2	1	1	1	2	1	1
Myanmar	100 %	46 %	11	6	6	6	6	3	3	3	3
China	29 %	3 %	7	8	12	8	8	7	19	7	7
Indonesia	99 %	67 %	5	4	5	3	3	3	5	2	2
Laos	100 %	83 %	3	2	2	2	2	1	1	1	1
Cambodia	100 %	61 %	3	2	2	2	2	2	2	1	1
India	70 %	4 %	2	1	1	1	1	0	1	0	0
Malaysia	100 %	57 %	1	1	1	1	1	1	1	0	0
Australia	18 %	18 %	46	53	82	52	69	53	89	52	73
New Zealand	85 %	82 %	1	1	5	1	2	1	8	1	2
TOTAL			407	361	498	275	296	355	583	230	254

production and possibly put pressure on tropical forests. The higher those pressures, the higher the need to double-check with the ecological criteria and their translation in the local or national environmental regulations (according to slopes, rivers, etc.).

This approach – where land-use competition between food and energy is considered settled by excluding agricultural land from computations of bioenergy potential – is clearly limited. However, projections of agricultural land requirements depend on a set of assumptions, mainly on yields, that would need to be revised after the local characteristics concerning land allocation have been investigated.

One further step to the approach described would then be to go back over the IMAGE assumptions regarding the yields and the other parameters of the model's land cover projections for the regions where some significant potential has been identified. Such feedback would allow the yield assumptions to be linked to the land availability assessment.

We shall illustrate the importance of assumptions on the agricultural yields for the assessment of the biofuel potential in the next section.

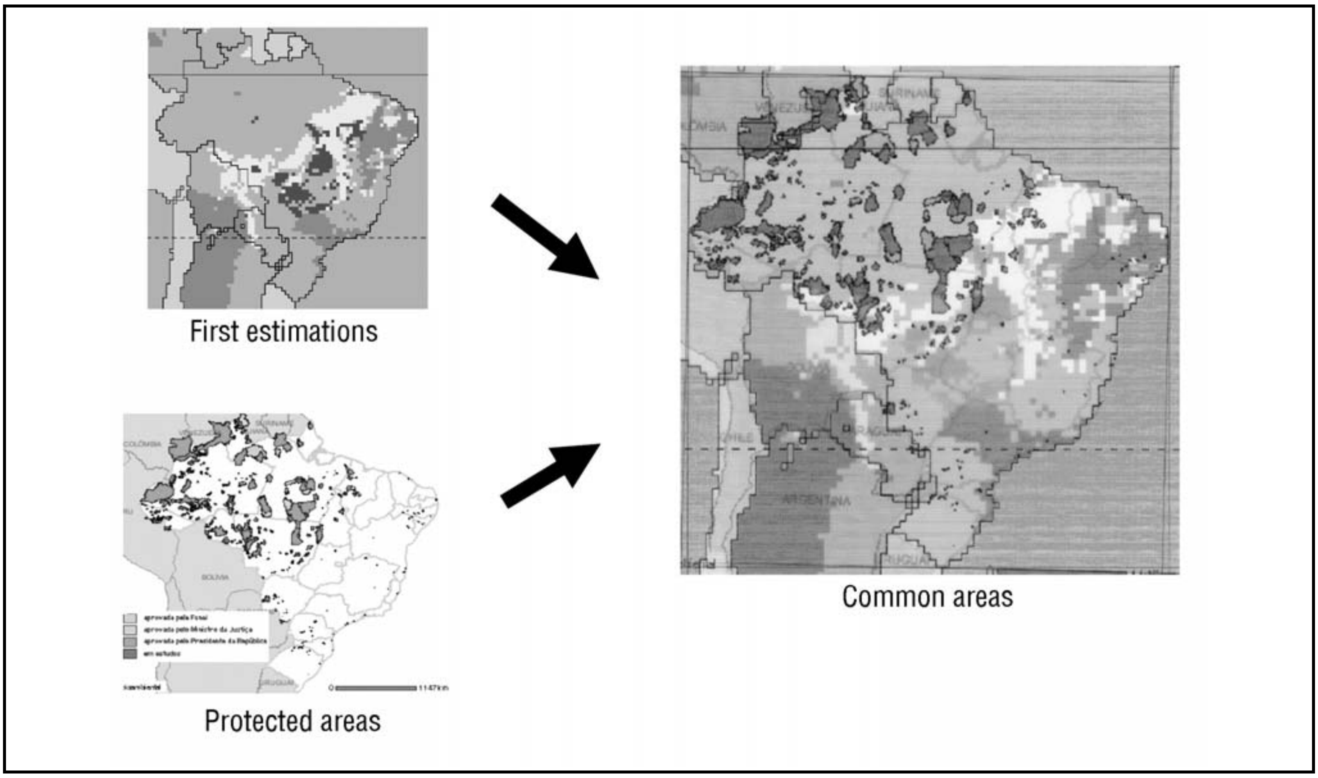

Figure 2. Comparing the initial estimation with local information

2.2. Feedback study on agricultural requirements for fulfilling estimated bioenergy potentials by 2050 [Griffon, 2006]

The feedback study considers the whole world as five regions: four regions with developing countries (Asia (excluding West Asia), Latin America, West Asia and North Africa (WANA), Sub-Saharan Africa) and one region covering the OECD countries.

Considering food requirements and their evolution by 2050, as forecast by the FAO, the necessary increase in cultivated land is first computed using current yields. Land requirements exceed the area suitable for agriculture, even when encroaching on protected areas. Thus, possible yield increases are considered, first due to irrigation only, further considering limitations in the availability of water resources: water that can actually be used is only a percentage (40 %) of the theoretical water potential, itself only a percentage (20 %) of the renewable water.

At this stage, Asia and WANA still have deficits; Latin America could compensate them at the current agricultural technology level.

The next stage consists of adding the bioenergy demand.

International Institute for Applied Systems Analysis (IIASA) and Dessus energy scenarios [Nakicenovic et al., 1998; Dessus et al., 1992; Dessus, 2003] are considered: they state that about 25 % of the world energy supply by 2050 could be renewable, out of which 80 % could be produced from biomass.

Globally, this would imply some 180 PJ to 270 PJ of biomass energy production falling under the 5 considered regions.

The assumptions about the average bioenergy production yields per hectare differ according to regions because of the different biomass feedstocks considered for biofuels. The areas required to produce bioenergy are computed given those assumptions.

Summing the areas required to meet food requirements (according to the FAO scenarios) and the areas required to meet energy requirements (according to IIASA and Dessus scenarios) shows that even sacrificing tropical forests will not be sufficient to meet both the food and the energy needs at the current technology levels (yields).

The required increases in agricultural yields by 2050 are then computed in each region both for the rain-fed and the irrigated agriculture cases (see Table 3).

Quite optimistic energy scenarios such as IIASA's and Dessus's (biomass providing 20 % of world energy consumption) imply agricultural yield improvements (through breeding, fertilization, herbicide application, etc.) within a range of 25 to 60 % in 50 years (an average of 0.45 to 0.94 % annual increase from 2000 to 2050).

The corresponding efforts for the increase of yields differ among regions, depending on the yields already attained and the necessary improvements.

- In Asia, yields have doubled in 30 years and are expected to increase by 50 % in the next 50 years, which would be rather difficult as yields have already attained high levels.
- In Latin America, yields have increased by 20 % in 30 years and could easily be multiplied by two or more.
- In North Africa and the Middle East, yields have not increased much in the past and can hardly increase more.
- In Sub-Saharan Africa, yields have increased by less

Table 3. Yields required to achieve biomass needs in 2050

Year		Asia	Latin America	WANA	Sub-Saharan Africa	OECD	CIS
2000	Food production (Mt)	1800	272	154	862	/	/
	Area cultivated for food (Mha)	439	203	86	228	387	265
	Area for total production	486	766	99	831	574	397
	Irrigated area	161	8, 5	25	5	-	-
	Increase in irrigated area	+44 to +89	+8 to +16	+5 to +25	+5 to +12	+18 to +53	+2 to +8
	Increase in production in irrigated area (Mt)	+100 to +280	+20 to +60	+4 to +24	+30 to +70	/	/
2050	Area for energy (Mha)	25	120	0	120	150	150
	Area irrigated	250	26	49	17	-	-
	Area rain-fed for food	210	620	50	694	-	-
	Yields of rain-fed crops (t/ha)	5.5	2.15	2	1.8	-	-
	Production of rain-fed crops (Mt)	1150	1338	100	1265	-	-
	Yields of irrigated crops	8	7	5	5	-	-
	Production of irrigated crops (Mt)	2000	182	245	85	-	-
	Total crop production (Mt)	3150	1520	345	1350	/	/
	Food needs (Mt)	4150	520	390	1350	/	/
	Total biomass energy surplus (+)/ deficit (-) (PJ)	-33	+22	/	+11	/	/
	Total food surplus (+)/ deficit (-) (Mt)	-1000	+1000	-45	0	+50	+150
=>	Increase in rain-fed yields 2050/2000	≈40 %	¢60 %	≈30 %	≈55 %	/	/
	Corresponding linear improvements (gain of kg/ha/yr)	0.044	0.026	0.012	0.02		
	Increase in irrigated yields 2050/2000	≈30 %	≈40 %	≈25 %	≈25 %	/	/
	Corresponding linear improvements (gain of kg/ha/yr)	0.048	0.006	0.025	0.025		

than 20 % in 30 years. The improvement potential is high but realisation is hampered by institutional problems.

Such a scenario would require very large investments in:

- irrigation with new technologies for water intensification;
- transport infrastructure to reach remote areas to be put into production; and
- research and technology transfer reducing production costs and negative environmental externalities and allowing sustainable agricultural livelihoods in currently very poor areas.

There are many quantified assumptions to review and perhaps modify in this study, whose results at this stage are not worth as much discussion as its methodology. Its main purpose is to make explicit the yield assumptions behind the land cover projections on which the estimation of potential is based, so as to better inform the issue of competition for land use instead of settling it right away by discarding the use of agricultural land for biofuels as in our first study.

Expanding crop and plantation areas for energy production might indeed worsen the competition for land between agriculture, forests and urban sprawl. The issue of frontiers of various land uses moving along the lines shown in Figure 3, as well as the possible overlapping of those frontiers in the case of agro-forestry or multiple cropping, merits documentation and debate.

By increasing the pressure on land uses, bioenergy requirements added to food requirements might well act as the necessary driver to increase agricultural yields so that the expansion of agricultural lands threatening forests and protected areas is avoided. The remaining burning issue would concern water requirements for the proposed land uses. Indeed competition may not only occur for the land but also, and maybe primarily, for water. Moreover, theoretical water requirements may be overtaken by actual use as can currently be observed for food crops.

To further debate the shifting of land-use frontiers and how bioenergy could be integrated into agricultural policy considerations, one needs to investigate the issue at the national level, given each country's characteristics in terms of estimated land potentials but also in terms of appropriate technologies.

3. Biomass and biofuel potentials

The estimates of potential biomass and the corresponding potential biofuels take into account the information available on land cover and uses and the potentials corresponding to the land areas possibly appropriate for producing biofuels.

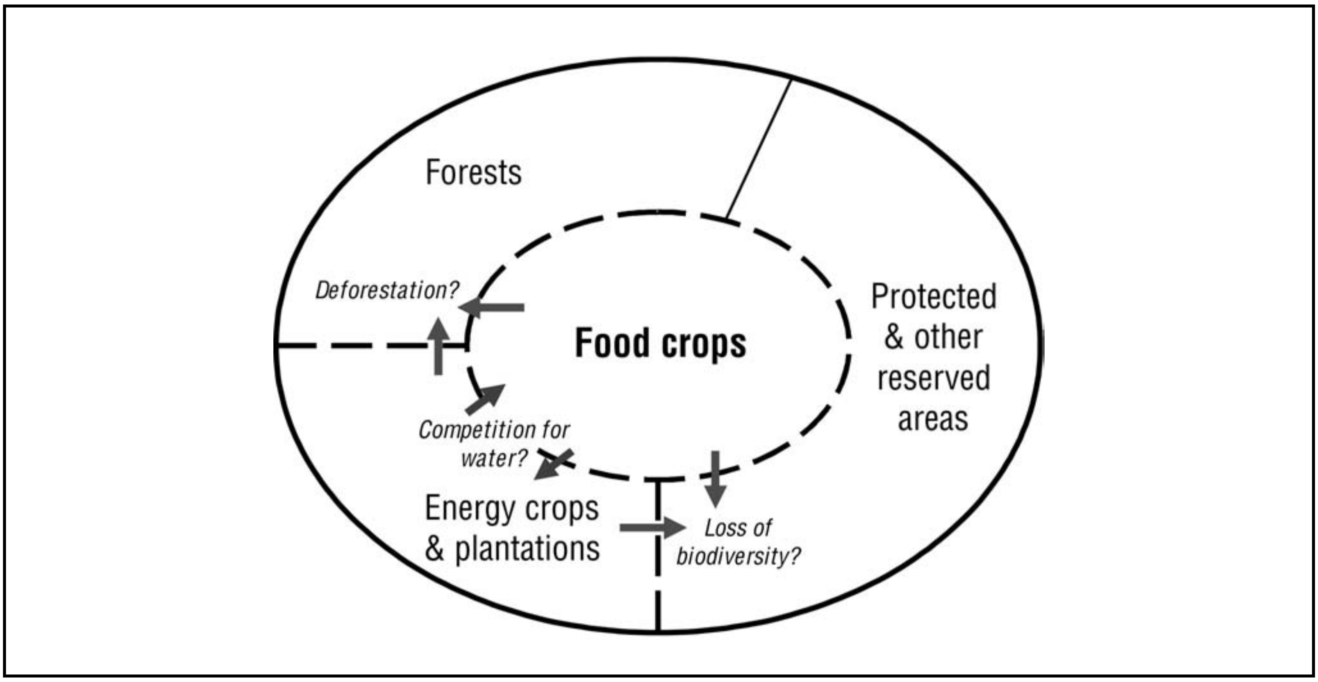

Figure 3. The shifting of land-use frontiers

The estimates of biofuel potentials must also consider the technical choices for producing biofuels.

3.1. Technical choices and land availability for energy plantations

Conventional biofuels consist of ethanol or biodiesel produced from dedicated crops (sugar cane, maize, rapeseed, etc.), converting sugar, starch and vegetable oils into alcohol and ester, as specified by Girard and Fallot [2005]. Within these first generation biofuels, rather low biofuel outputs can be expected since only a small part of the plant is used. In developing countries where food security may not be achieved, the use of such food or feed products for energy application is sensitive, particularly if rich soils are concerned.

To illustrate what conventional biofuel production systems would mean for soil use, let us consider two contrasted countries in terms of economic and social situations: India and Burkina Faso. For these developing countries, we estimate the areas of energy crops required to substitute 20 % of the oil that is currently consumed.

Table 4 shows that for both India and Burkina Faso, the requirements to achieve the 20 % goal would represent between 25 and 80 % of the presently cultivated area and the land use competition with food crops would be unreasonably high, not to mention the water issue. Additionally, the current level of the fuel consumption in these countries may be considered low, with basic energy needs not remaining fully satisfied, especially in some rural areas. With increasing atandards of living in the future, fuel consumption is bound to rise substantially.

For these reasons, conventional biofuels might be irrelevant on a large scale for most, if not all, countries in tropical regions (plus East Asia, the Pacific and non-tropical South America).

The alternative options realistically feasible within the next decade are based on second generation biofuels, including biochemical conversion of cellulose and thermochemical processing of lignocellulosic biomass. The advantage of these options results from the use of the whole plant and not only its oily or carbohydrate fraction, allowing larger productivity per unit cultivated area. The figures in Table 5 consider a pyrolysis/ gasification Fischer-Tropsch (FT) synthesis supply chain with a global biomass for volume efficiency of 20 % (energy efficiency amounts to about 50 %) and energy plantations with an average productivity of 15 t/ha/year. FT diesel productivity can then reach 3,500 l/ha.

Surprisingly, the areas required in both India and Burkina Faso represent approximately the same, small (5 %), percentage of the currently cultivated areas. In that case, the land competition issue would be less sensitive than with first generation biofuels. The FT option looks more feasible particularly because the required areas for the plantations can have poorer soils than those for the first generation biofuels. However, the food-energy competition for water would remain.

The numbers above are just indicative of the orders of magnitude. They do not account for future increases in food and energy demand and suggest greater attention be paid to second generation biofuels for developing countries where land use competition between food and energy is a problem.

3.2. Energy plantations: potentials and areas

Seen as a promising route to investigate, the supply chain for Fischer-Tropsch biodiesel is selected as the technical option to stress the implication of the technology choice for the feasibility of biofuels.

However, the implementation of FT means large-scale biofuel production units, which would require large amounts of biomass to be collected and transported with the corresponding costs.

Table 4. Examples of oil substitution by conventional (first generation) biofuels

Parameter	India	Burkina Faso
Population (millions, 2005)	1103.6	13.9
Oil consumption (thousands of barrels[1] per day)	2,200 in 2003 2,800 by 2010	8.9 in 2002
Substitution rate of fossil fuels by biofuels	20 %	20 %
Biofuels required (Ml)	32,500	515
Land area required for biofuel (Mha)	50 (sunflower) 150 (cottonseed)	0.8 (rapeseed) 2.4 (cottonseed)
Cultivated area (Mha)	180.1	3.3

Source: Calculated from figures from [EIA-OES, 2004]

Note

1. See Note 6 at the end of this article.

Table 5. Examples of oil substitution by FT biofuels for India and Burkina Faso

Criteria	India	Burkina Faso
Population (million) 2005	1103.6	13.9
Oil consumption (thousand of barrels per day)	2,200 in 2003 2,800 by 2010	8.9 in 2002
Substitution rate of fossil fuels by biofuels	20 %	20 %
Biofuels required (Ml)	32,500	515
Land area in plantations required (Mha)	9.3	0.15
Cultivated area (Mha)	180.1	3.30

As Table 6 shows, the capacity of the smallest FT units is around 10,000 b/d (barrels[6] per day), which can be obtained from 0.8 Mm^3 of synthesis gas. 10,000 b/d capacity can probably be considered the minimal economically viable size nowadays with regards to fossil fuel resources. Such an FT plant corresponds indeed to a production cost of US$ 15/GJ (with $ 3.75/GJ price for biomass)[7]. For comparison purposes, we should mention that US$ 50 and 65/barrel respectively correspond to a price of 8.75 and 11.25 US$/GJ for crude oil, to which no more than 0.75 US$/GJ should be added to account for refining costs.

To efficiently supply a FT biofuel production unit, two scenarios can be considered, both relying on energy plantations.

A. Centralized FT biodiesel production units, directly supplied with raw biomass.

B. Semi-decentralized production, with the pre-conditioning of biomass into liquids by means of flash pyrolysis units located in biomass-rich places, then transport of the energy-concentrated intermediate to a gasification/FT synthesis centralized unit. The idea here is to reduce raw biomass transport costs associated with converting biomass at large-scale facilities [Bridgwater, 1999]. Other intermediate products than pyrolysis oil are imaginable, such as pellets, densified biomass, etc.

With a 10,000 b/d FT plant, Scenarios A and B respectively imply:

A(10). Directly supplied, raw biomass required would represent 2.3 Mt of dry wood per year. With an average plantation productivity of 15 t/ha/yr, this would mean 160,000 ha of plantations (eucalyptus, pine, or acacia). For comparison purposes, in Brazil nowadays, large steel industries are generally managing 40,000 ha of eucalyptus plantations to produce the charcoal required for pig-iron production.

The biomass supply zone would then be within a radius of 31 km around the FT plant if plantations cover 50 % of the area, of 70 km around the plant if the plantations cover 10 % of the area. Preliminary studies in Brazil [Aimola and Piketty, 2005] show how the availability of such areas is restricted by institutional factors (laws, measures at various decision levels, etc.), socio-environmental factors (green parties, social movements, etc.), land issues (property rights definition, land conflicts, etc.) and economic factors. Increasing the number of feasible units worldwide may therefore be a question of reducing the supply radius by decentralizing the initial biomass transformation.

B(10). In the case of decentralized units, 80 flash pyrolysis units with a 100 t/d capacity and 70 % efficiency would be required to handle the 2.3 Mt/year of biomass being considered.

The biomass supply zone of each pyrolysis unit would then be 2000 ha producing 30,000 t of wood per year. Such an area is equivalent to that of a large farm, relatively common worldwide.

Up to now, research in flash pyrolysis has been essentially devoted to oil quality for substitution for fossil fuels after hydro-cracking, limiting its efficiency due to the very strict quality requirements. If FT could create good prospects with a wider spectrum for the bio-oil quality, some larger flash pyrolysis units could be reached, handling 1000 t/d of wood and a better yield (80 %). Such scaling-up would allow some 7 pyrolysis units to supply the 10,000 b/d FT plant with oil.

The semi-decentralized option enlarges possibilities as it reduces land availability constraints. Pyrolysis units could indeed be located in remote areas where biomass can be grown without competition, the oil being transportable over long distances with moderate cost impact. River and sea transport can even be considered [Hamelinck et al., 2005], as well as the railway network. The number of potential plants would be larger.

Another research orientation could be towards downsizing FT plants due to better product selectivity. If a FT plant could be operational at a size equivalent to that of the large refineries, 3,000 b/d, our two hypothetical scenarios with the same yields as A(10) and B(10) would become the following.

A(3). Centralized: 0.7 Mt wood required by FT plant, requiring a 47,000 ha plantation.

The biomass supply zone would be within a radius of 17 km around the FT plant if the plantations covered 50 % of the area and of 39 km around the plant if the plantations covered 10 % of the area.

B(3). Decentralized intermediate conversion: 25 flash pyrolysis units each requiring 30,000 t of wood per year from 2000 ha.

The downsizing of the FT unit would facilitate its replicability and lead us to consider some countries with land potential below 1 Mha (according to minimum rainfall and maximum population criteria explained above, Section 2.1). This would add 6 countries to the list of countries considered for further study on potentials: Ghana, Guinea-Bissau, Colombia, Laos, India, and Malaysia (see Table 2).

If a 3,000 b/d unit is feasible, an interesting question arises: would agricultural residues become a possible feedstock for FT biodiesel, for instance producing pyrolysis oils to be blended with the woody bio-oils?

The issue of biomass residues as energy sources is considered in Section 3.3 below.

3.3. Residues: potential and the availability issue

Agriculture and forestry generate residues, which can be used (by-products) or disposed of (wastes). Crop and the animal wastes are recognised as sources of environmental pollution and, therefore, efforts are made to use or recycle them. Agricultural residues have acquired considerable importance as biofuels for domestic cooking, industrial process heating, power generation, etc., and they are used directly as well as in briquetted form for a variety of energy end-uses.

The figures provided on potentials for energy are to be considered with care as there is no consensus among the attempts to estimate the global production and use of residues. A large range of estimates has been reported, varying from 20 to 200 EJ [Woods and Hall, 1994]. Three of these estimates are documented in Table 7.

Table 6. Existing FT plants (natural gas or coal)

Year	Industrial	Country	Production (barrel per day)
1975-1990	Shell, BP, Exxon...	USA	20-400 (pilot)
1985	Mobil	New Zealand	15,000
1992	Sasol	South Africa	24,000
1993	Shell	Malaysia	12,000
2003	Syntroleum	Australia	10,000
Future	Exxon, Shell, Total	Qatar	100,000

Residues are often the cheapest source of bioenergy and may present many opportunities for better utilization, before the dedicated energy forestry/crops play a greater role in the longer term. The expected increase in biomass energy derived from residues, particularly in the modern forms of biofuels, could have a significant impact not only on the energy sector, but also on the drive to modernize agriculture, and on rural development, thanks to the additional income residues could bring in and to the energy made available in rural areas.

Research focusing on the most promising residues usually focuses on residues from the sugar cane, pulp and paper, and sawmill industrial sectors. Bagasse, for instance, is produced at a rate of more than 300 Mt per year worldwide, mostly for use as fuel in sugar cane factories. The total energy content could represent a fuel production capacity greater than 1 Mb/d.

Using FAO data and residue/crop ratios, G. Vaitilingom at CIRAD carried out a survey of the potential availability of residues from tropical crops and ranked the fifteen largest countries by volume. The main results are given in Table 8. Rice husk and straw represent by far the largest potential as they represent a volume larger than 500 Mt/yr. Their real availability must face ecological and technical constraints, and competition with other uses. Still, there is no doubt that a considerable proportion of the residues is wasted or handled inappropriately, causing undesirable effects from environmental, ecological and food production viewpoints.

China and India present by far the largest crop residue potential. This is mainly due to the share of rice by-products, straw and husk, which represent 83 and 71 % of their respective potentials. Rice straw accounts for 56 % of the top ten global potential crop residues followed by bagasse (15 %), and rice husk and cotton stalks (10 % each).

Apart from the USA and Australia, the fifteen top countries in terms of tropical crop residue potentials are countries with considerable growth in energy demand and particularly electricity, with figures generally over 5 % per year. With such demand and the limited investment capacity of the utilities, independent power production

Table 7. Estimates of agricultural residue potentials

Authors	Potentials	Remarks
Smil, 1999	3.5-4 Gt 65 EJ	Crop residues
Hall et al., 1993	- 38 EJ	World's major crops (wheat, rice, maize, barley, and sugar cane), 25 % residue recovery rate
BTG, 2006	1.5 Gt 19.1 EJ	Practical potential based on FAO data and specific residue recovery rate

Table 8. Tropical crop residue potential in the 15 largest world producers in 2003 (Mt dry matter)

	Bagasse	Rice straw	Rice husk	Cotton stalks	Sorghum straw	Coconut husk + shell	Total dry matter
China	12.3	199.6	39.9	47.5	3.4	0.1	302.8
India	33.0	145.1	29.0	22.5	8.3	3.7	241.6
Brazil	55.0	14.9	3.0	9.0	2.4	1.1	85.4
Indonesia	3.3	60.8	12.2	0.1		6.2	82.6
Thailand	9.2	30.3	6.0	0.1	0.2	0.6	46.4
USA	3.6	11.8	2.3	31.4	12.8		61.9
Vietnam	2.2	40.6	8.1	0.1		0.4	51.4
Bangladesh	0.9	42.6	8.5	0.1			52.1
Pakistan	7.2	8.4	1.6	18.4	0.2		35.8
Malaysia	0.2	2.5	0.5			0.3	3.5
Philippines	3.8	16.3	3.2			5.5	28.8
Myanmar	0.9	24.8	5.0	0.5		0.1	31.3
Mexico	6.1	0.3	0.1	0.6	7.0	0.3	14.4
Australia	5.3	1.5	0.3	2.9	2.0		12.0
Colombia	5.0	2.6	0.5		0.3		8.4
Total Mt	147.5	602.1	120	133.2	36.6	18.3	1058.4
Total PJ	260	9840	1940	2410	610	360	34080

Source: Gilles Vaitilingom, CIRAD, with numbers from FAO, 2005

Note

The figures are the annual technical potential of the residues. Dry matter weight is used for a better comparison. Its higher heating value stands in a +/- 15 % range around an average of 16.9 GJ/t dry matter.

(IPP) schemes are generally promoted. Agricultural residues are found in rural areas and the easiest residues to collect and the cheapest part of them, namely residues of manufacturing facilities (e.g., waste wood from sawmills), are already concentrated. Decentralized heat and power production is most probably preferred to other types of energy conversion; agro-industries have themselves large heat and electricity needs which favour cogeneration schemes for self-generation, the excess electricity being sold to the grid. However, even if residues appear to offer globally low potentials for large-scale biofuel production for transportation, their contribution needs to be studied in local situations and also transitory situations before optimal investments can be effective.

The main issues to tackle when considering the use of residues for modern energy supply and intending to assess the potential residues could offer in addition to that from plantations are the following.

- The methodology and the assumptions for determining what is and what is not a recoverable residue. The estimates often vary by a factor of 5, due to variations in the percentages of residues assumed available, given the requirements for soil organic matter and soil erosion control, efficiency in harvesting, losses, non-energy uses, animal manure production, etc.

  Soil erosion prevention, agricultural pollution reduction, water resource management, etc., are considered some major goals for the 21st century. The use of agricultural residues for biofuel production, and on an industrial scale (owned by international corporations)

will face environmental preservation rules, viz., regarding the level of organic matter that directly controls the fertility and water storage potential.
- Locally, the existence of many other alternative uses: animal feed, animal bedding, fertilizers (dung).

To formulate and implement long-term strategies for the efficient and economic utilization of agricultural residues as feedstock for energy conversion and utilization, it is then important to estimate their monetary values in the various possible supply chains. This can be done in given economic environments, for instance through a backward computation, starting, for each alternative supply chain, from the maximum market price that the end-product made of residues can have, given the competition from equivalent products made from other resources.

4. Summary

Biomass resources, being potentially one of the world's largest and most sustainable (renewable) energy sources, with 220 oven-dry Gt of annual primary production [IEA, 2005], deserve special attention. The corresponding annual bioenergy potential is about 2,900 EJ out of which only a fraction can be considered available for energy on a sustainable basis and at competitive prices.

The estimation of this fraction and of the resulting biofuel potentials follows a multi-stage approach, the first two stages of which have been presented for discussion in this paper.

After providing insights on obtaining spatial data to be used as a basis for projections of land uses and subsequent potential land availability, Section 2 proposed a methodology for the estimation of land potentials for biofuels. It raised the methodological issue of the appropriate scale levels for spatial analysis: successive proposed steps intending to narrow down the scale, namely for validation from global to local and back to global for aggregate assessment of potential contribution to energy challenges. Further, maps can be superimposed to define national strategies in which energy is only a component among other priorities, in terms of country planning for instance.

Section 3 on biomass and biofuel potentials provided order of magnitude estimates for biofuel potentials and illustrated that, when dealing with biofuel potentials, agricultural and energy choices are narrowly linked within issues of infrastructure for development. We showed how, by downsizing biofuel plants or pre-treating biomass, more countries become potentially interested in growing biofuel for transportation on a large scale. ■

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Notes

1. ESD dedicated a special issue (March 2006) to the subject of bioenergy trade.
2. In large countries such as Brazil and India where the states develop their own public incentives for bioenergy development, further studies are required at the state level as well.
3. The IMAGE model also includes bioenergy crops in agricultural lands. They are "business as usual" bioenergy crops, depending on the scenario. They are not the result of a voluntaristic policy for bioenergy. We focus on additional biofuel production.
4. Angola, Democratic Republic of Congo, Central African Republic, Zambia, Mozambique, Tanzania, Guinea, Madagascar, Cameroon, Côte d'Ivoire (Ivory Coast), Congo (Brazzaville), Benin, Gabon, Brazil, Bolivia, Venezuela, Paraguay, Ecuador, Myanmar, Indonesia, Cambodia, New Zealand.
5. Yellow and red mean more optimistic and more pessimistic with respect to the global environment.
6. 1 barrel of crude oil = about 136 kg.
7. These numbers were given during the Synbios international conference on Second Generation Automotive Biofuels, Sweden, 18-20 May, 2005.

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