Mapping land suitability at worldwide scale for fuelwood plantations

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Plantation d'*Eucalyptus sp*. à Pointe Noire (Congo).
Photo L. Gazull.

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RÉSUMÉ

CARTOGRAPHIE DE LA DISPONIBILITÉ DES TERRES À L'ÉCHELLE MONDIALE POUR LES PLANTATIONS DE BOIS ÉNERGIE

Une cartographie du potentiel de plantations arborées pour un niveau de rendement de biomasse ligneuse est présentée selon une approche biophysique. Trois genres botaniques ont été retenus comme aptes pour la production de bois-énergie : *Acacia*, *Eucalyptus* et *Pinus*. L'intérêt des résultats réside dans l'utilisation de données géoréférencées, à 1 km de résolution, de précipitations, de températures et de types de sol. En accord avec ces paramètres ayant un impact significatif sur la distribution des espèces, des enveloppes bioclimatiques ont été générées à l'aide d'un Système d'information géographique (Sig). Le résultat est une combinaison de la moyenne des températures maximales du mois le plus chaud, de la moyenne des températures minimales du mois le plus froid et de la moyenne des précipitations annuelles. Ces critères sont retenus en considérant les contraintes édaphiques pouvant atténuer la productivité de biomasse. À l'échelle mondiale, pour les espèces retenues, les zones de plantations potentielles sont de l'ordre de 253 millions d'hectares (Mha) pour les espèces du genre *Acacia*, de 441 Mha pour les espèces du genre *Eucalyptus* et de 560 Mha pour les espèces du genre *Pinus*. Des cartes à l'échelle mondiale sont fournies pour des productions de 6 à 9 tonnes de matière sèche par hectare et par an. Le total des surfaces disponibles pour la plantation des espèces des trois genres considérés est de l'ordre de 600 Mha (6 millions de km²). La limite des bases de données affecte la validité de ces résultats qui nécessitent forcément des études complémentaires afin d'affiner ces estimations tout en introduisant la notion d'usage des sols à celle des catégories d'occupation des terres.

Mots-clés : bioénergie, usage des sols, contrainte édaphique, enveloppe bioclimatique, SIG, potentiel de plantation arborée, biomasse ligneuse.

ABSTRACT

MAPPING LAND SUITABILITY AT WORLDWIDE SCALE FOR FUELWOOD PLANTATIONS

Locating potential tree-planting based on biogeophysically assessment of the range of potential yield of woody biomass is introduced. Three genera of trees have been identified as relevant to energy plantations: *Acacia*, *Eucalyptus* and *Pinus*. The interest of the results lies in the use of a spatial analysis at 1 km resolution. This approach uses georeferenced data as input for rainfall, temperatures and soil types. In a Geographical Information System (GIS) environment, bioclimatic envelopes are generated. The result is a global combination of mean daily maximum temperature of the warmest month, mean daily minimum temperature of the coldest month and mean annual rainfall which seem to have impact on the distribution of species. These criteria are retained for each species when considering edaphic constraints which adversely affect biomass productivity. At a worldwide scale, for selected species, the potential tree-planting areas are about 253 million hectares (Mha) for *Acacia* species, 441 Mha for *Eucalyptus* species and 560 Mha for *Pinus* species. Maps at worldwide scale are provided with a yield of 6-9 tons of dry matter per hectare and per year. The total of the areas available for plantations is about 600 Mha (6 million km²) of potential tree canopy cover. The limit of databases affects the validity of results and further studies are needed to refine these estimations with a mix between land use and land cover categories.

Keywords: bioenergy, land use, edaphic constraint, bioclimatic envelope, GIS, potential tree-planting, woody biomass.

RESUMEN

CARTOGRAFÍA MUNDIAL DE TIERRAS DISPONIBLES PARA PLANTACIONES DENDROENERGÉTICAS

Se presenta el potencial de plantaciones arbóreas basándose en la evaluación biofísica del nivel de rendimiento de biomasa leñosa. Se seleccionaron tres géneros botánicos adecuados para la producción energética: *Acacia*, *Eucalyptus* y *Pinus*. El interés de los resultados radica en la utilización de un enfoque espacial con datos de 1 kilómetro de resolución espacial. Este enfoque utiliza datos georeferenciados de precipitaciones, temperaturas y tipos de suelo. En el entorno de un Sistema de Información Geográfico (SIG), se delimitan las envolturas biogeográficas. El resultado es una combinación global de los promedios anuales de temperaturas del mes más cálido, temperaturas del mes más frío y precipitaciones, que parecen tener un impacto en la distribución de las especies. Dichos criterios se seleccionaron considerando las restricciones edáficas que perjudican la productividad de biomasa. A escala mundial, para las especies seleccionadas, las zonas de plantaciones potenciales son de aproximadamente 253 millones de hectáreas (Mha) para *Acacia*, 441 Mha para *Eucalyptus* y 560 Mha para *Pinus*. Se proporcionan mapas a escala mundial para producciones de 6 a 9 toneladas de materia seca por hectárea y año. El total de las superficies disponibles para plantaciones es de unos 600 Mha (6 millones de km²) de cobertura arbórea potencial. El límite de las bases de datos afecta a la validez de los resultados, haciendo necesaria la realización de estudios complementarios para afinar estas estimaciones con una combinación entre el uso de suelos y las categorías de ocupación de tierras.

Palabras clave: bioenergía, uso de suelos, restricción edáfica, envoltura bioclimática, SIG, potencial de plantación arbórea, biomasa leñosa.

Introduction

Wood has always been the most important energy source for humans until oil became widely available. Facing the rising fossil fuel prices and the announcement of the oil resource depletion, alternative energy sources and in particular wood energy is the subject of renewed interest.

As a source of bioenergy, woody biomass offers a significant advantage over many agricultural crops, which usually have to be harvested annually, increasing the risk of oversupply and market volatility (Perley, 2008). Woody biomass and other perennial plants can be advanced or delayed depending on price fluctuations and trees can grow on marginal land unsuited for food production (Gabus, Hawthorne, 2008).

Wood products have multiple final uses such as power production, pulp, panels and timber production (Fao, 2008). Trees can provide the energy needed to produce heat, electricity or second generation biofuels (biochemical and thermochemical conversion off non-food plants). Since the 1970's and their oil shocks, many studies attempted to estimate the amount of woody biomass for energy production that could be produced on the horizon of 30, 50 or a 100 years (Hoogwijk *et al.*, 2005). The contribution of biomass in the future global energy supply is reviewed in many studies. The 17 earlier studies compiled by Berndes *et al.* (2003) have arrived at widely different conclusions. Planting trees for energy is not an innovation for over 40 years; many countries have developed this type of planting to stop deforestation for the supply of firewood.

At a worldwide scale (in boreal, temperate and tropical climates), three genera of trees have been identified as particularly relevant and frequently used to energy plantations:

- *Acacia* genus is a characteristic of arid, semi-arid and much sub humid climatic regions and colonizes lands of low fertility unsuited for agricultural crops;
- *Eucalyptus* genus is characterized by its ability to provide high yields on short rotations, for producing good fiber and for its rapid growth;
- *Pinus* genus is the most common genus in the world; it can adapt to a large edaphic range and thus grows in different soils.

The other genera of trees have less efficient productivity and several drawbacks in terms of length of rotation or of specific needs. For the first stage of exercise, the study doesn't take account for locally interesting trees in this global assessment.

The aim of this study is to locate suitable areas to plant trees and to estimate medium and long term worldwide dedicated biomass yield for second generation bioenergy supply chain. The interest and originality of these results (compared to existing results) lies in the use of a spatial approach at 1 km resolution, producing values and maps for the three genera studied.

At worldwide scale, in spite of the low accuracy of land cover layer affects the validity of results, this spatial approach of assessment of the biomass world potential of trees growth (*Pinus*, *Acacia* and *Eucalyptus*) is used for drawing attention to the each country's potential for future analyses which would be conducted at a fairly more local scale with much higher resolution. Thus, a GIS-based method is used that enables a biogeophysically-based assessment of the range of potential yield of woody biomass, delimiting their bioclimatic envelopes. This approach uses georeferenced data as input for rainfall, temperatures and soil types while simultaneously excluding several spatial variables from production areas.

Plantation d'*Acacia auriculiformis*
en République démocratique du Congo.
Photo D. Louppe.

Land Suitability Evaluation Methodology

Hutchinson (1957) defined the fundamental ecological niche as comprising those environmental conditions within which a species can survive and grow. Bioclimatic envelopes can be defined as constituting the climatic component of the fundamental ecological niche (Pearson, Dawson, 2003). Tan *et al.* (2000) indicate that the climate pattern is one of the most important components for land productivity assessment. Drawing on this relationship between distribution and climate the method consists in favourable conditions to estimate the potential areas available for plantations at a worldwide scale while simultaneously including other environmental factors that influence the distribution of plant species, such as soil type.

Gridded spatial interpolated climate data such as mean daily maximum temperature of the warmest month, mean daily minimum temperature of the coldest month and mean annual rainfall which seem to have impact on the distribution of species, allowed to define the spatial distribution of bioclimatic envelopes (Eldin, 1971; Emberger, 1954), where species evolve at different level of production without any irrigation.

From the existing scientific literature, and from a field survey conducted in 2006 by the forestry department of the Food and Agriculture Organization of the United Nations (FAO, 2006), bioclimatic criterions were defined for a minimum yield of 6 tons of dry matter per hectare and per year (t.DM/ha/yr) for *Pinus* (with 14 years rotation period) and 9 (t.DM/ha/yr) for *Eucalyptus* and *Acacia* (with 7 years rotation period). This threshold matches to the current average yields observed all over the world (table I). This yield can seem weak in comparison with some productivities attained in plantations in Brazil or in Southeast Asia (30 t.DM/ha/yr), but it corresponds to actual sylvicultural practices and know-how on the global scale. Factors affecting yield, such as nutrient limitations or pests, were not considered. Observation data mainly come from a 2006 global surveys of existing plantations directed.

Table I.
Average observed yield (FAO, 2006).

Genus	Species	Continent	Observed yield in plantation (t.DM/ha/yr)*	Mean rounded
Acacia	*nilotica*	Africa	7	9
	mangium	Asia	12	
Pinus	*radiata*	South America	10	6
	taeda	Norht America	4	
	radiata	Australia	8	
	patula, eliottii	Africa	6	
	sylvestris	Europe	4	
	massoniana	Asia	4	
Eucalyptus	*ssp.*	South America	14	9
	globulus	Australia	9	
	grandis	Africa	10	
	grandis	Asia	4	

* Yield in tons of dry matter per hectare and per year (t.DM/ha/yr).

Bioclimatic parameters

The bioclimatic database is based upon the climate directories services of WordClim database (HIJMANS *et al.*, 2005; JONES, GLADKOV, 2003)[1] which climatic data were collected according a large number of sources and interpolated with quality control model from weather station network with time series of daily maximum, minimum temperature and precipitation. As for topographic data, it is originating from the USGS Digital Elevation Model GTOPO30[2].

Annual precipitation (P mm)

Although their biological interest is less clear than the summer rainfall, the annual rainfall should be taken into account because it is the data that is both easier to find and often most reliable amongst data from meteorological network. The variability of annual rainfall and its relative importance, represented by a map in figure 1, is the mean of the precipitation P (expressed with millimetres per year, mm/yr) observed between 1950 and 2000.

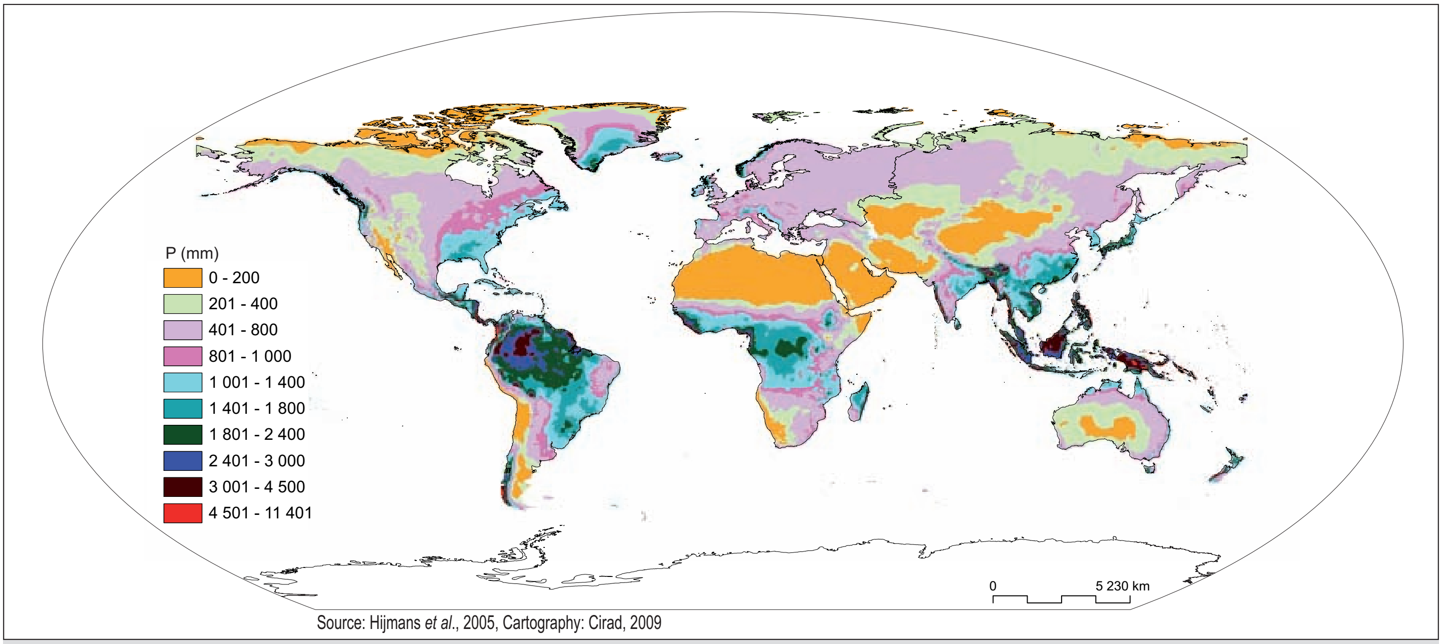

Figure 1.
Map of the precipitation (P expressed with millimetres per year, mm/yr) based on the mean annual precipitations recorded during the 1950-2000 period.
Source : HIJMANS *et al.* (2005). Cartography produced by CIRAD (2009).

[1] List of international databases used for the study :
GHCN: Global Historical Climatology Network, 1997.
WMO: Climatological Normals (CLINO) for the period 1961-1990. World Meteorological Organization: Geneva, Switzerland, 1996.
BOM: The Australian Data Archive of Meteorology. Bureau of Meteorology, Commonwealth of Australia: Melbourne, Australia, 2003.
INTECSA: Estudio de Climatología. Plan director Global Binacional de Protección – Prevención de Inundaciones y Aprovechamiento de Los Recursos del Lago Titicaca, rıo Desaguadero, lago Poopo y Lago Salar de Coipasa (Sistema T.D.P.S). INTECSA, AIC, CNR: La Paz, Bolivia, 1993.
CIAT: A database assembled by Peter G. Jones and collaborators at the International Center for Tropical Agriculture (CIAT) in Colombia. This database has data for the (sub) tropics only and is particularly data rich for Latin America.
[2] USGS-GTOPO30, 1996. http://eros.usgs.gov/products/elevation/gtopo30/gtopo30.html.

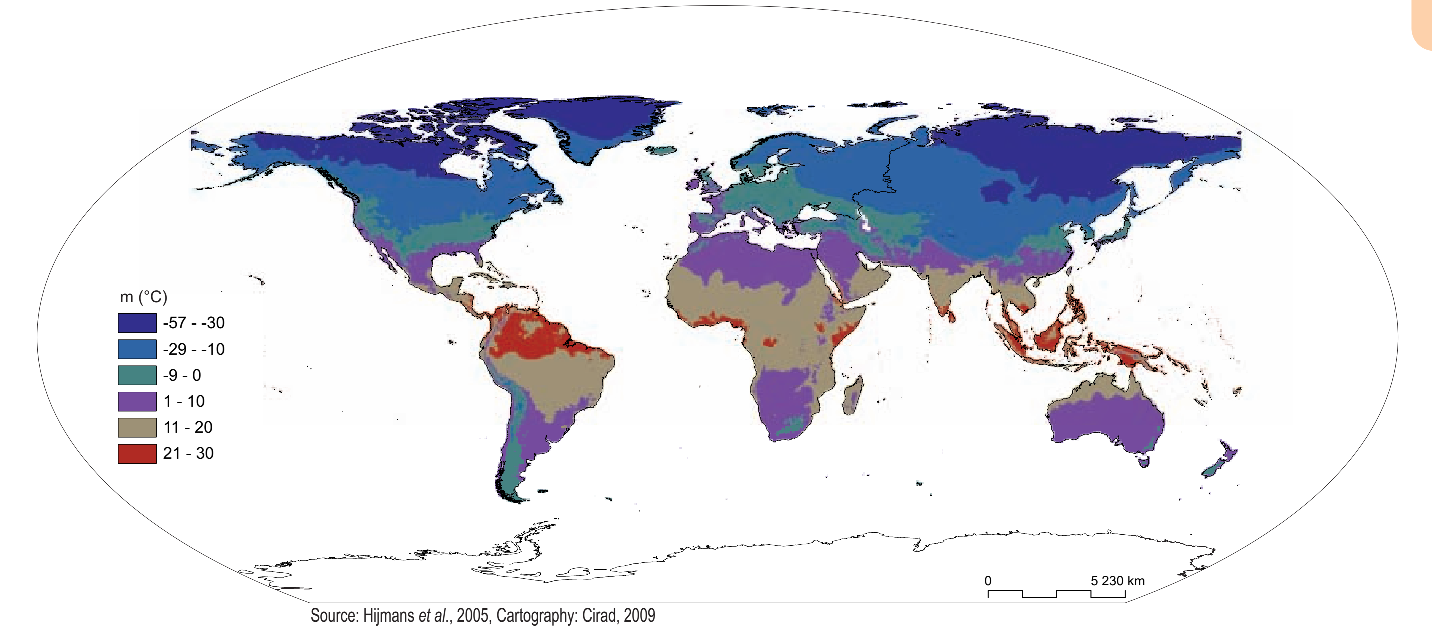

Figure 2
Map of the mean daily minimum temperature of the coldest month from 1950 to 2000.
Source : Hijmans *et al.* (2005). Cartography produced by Cirad (2009).

The winter thermal stress, cold tolerance (m °C)

The winter thermal stress and cold tolerance m (expressed with Celsius degrees, °C) was define with worldwide data recorded from 1950 to 2000. Some species of the three genera of tree considered tolerate low temperatures while others are highly susceptible to cold. At worldwide scale it is widely believed that plants grow when the monthly average temperature reaches or exceeds 5 °C, which is equivalent to 0 °C of the mean of the monthly daily minimum (Le Houérou, 1989). There are wide differences between the species since photosynthesis is still likely to take place in temperatures of -5 °C in several species of *Picea sp.*, while most tropical species are active only when temperature reaches 10 to 15°C. The most sensitive and most accurate criterion for measuring the thermal stress tolerance winter is undoubtedly the mean daily minimum temperature of the coldest month. The variability of this criterion is mapped on a worldwide scale (figure 2).

The summer thermal stress (M °C)

The dry season refers to conditions of summer heat stress more or less intense. It is the hot and dry winds that dry the atmosphere and impact a water deficit on the vegetation. To better resist to strong wilting, some species limit their transpiration by closing progressively their stomata.

To better take into account the species 'sensitivity to warm and sunny days, the mean daily maximum temperature of the warmest month M (expressed with Celsius degrees, °C) is mapped (figure 3), reflecting the limits of tolerance to the intensity and duration of the warm period, not to evaluate it.

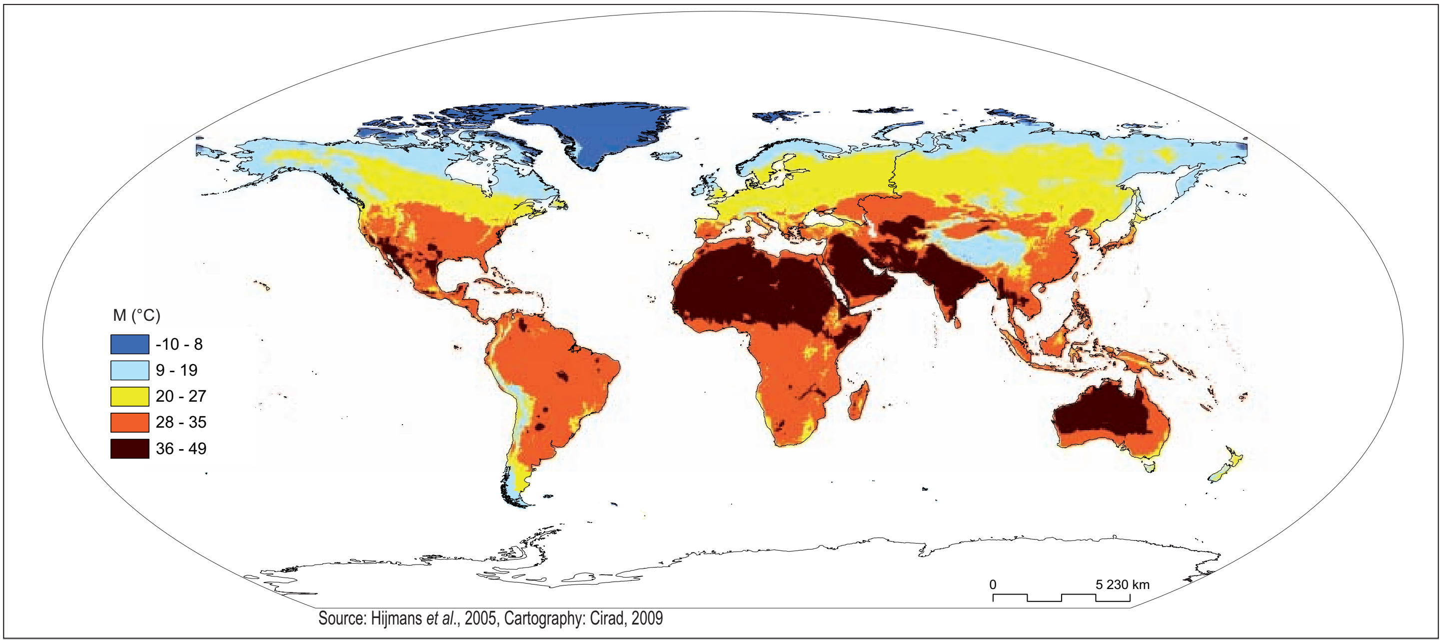

Figure 3.
Map of the mean daily maximum temperature of the warmest month M (expressed with Celsius degrees, °C) recorded between 1950 and 2000.
Source : Hijmans *et al.* (2005). Cartography produced by Cirad (2009).

Bioclimatic envelopes for biomass yield

The objective is to create a georeferenced map of potential biomass yields for each genus from the existing scientific literature and from a field surveys. Bioclimatic criterions available for a minimum yield of 6-9 t.DM/ha/yr were delimited and used to calculate the spatial distribution of the three genera. Data have been collected according a conglomerate of references:

- Genus *Acacia* (*A. mangium*, *A. auriculiformis*) where yields reach a sustainable 9 t.DM/ha/yr (Aciar, 1986; Vitousek, Sanford, 1986; Sim, 1987; Pandey, 1987; Bernhard-Reversat *et al.*, 1993):
    - Subsistence area: 110 < P < 4,000 mm and m > -10 °C and M < 45 °C.
    - Production area to reach 9 t.DM/ha/yr delimited with: 900 < P < 4,000 mm and m > 15 °C and M < 38 °C.

- Genus *Eucalyptus* (*E. Grandis*, *E. urophylla*, *E. globules*, *E. gundal*, *Eucalyptus spp*) where yield reach a sustainable 9 t.DM/ha/yr (Maxwell, 1982; Loumeto, 1986; Pukkala, Pohjone, 1990; Bouvet, Andrianirina, 1990; Baker *et al.*, 2005; Christersson, Verma, 2006):
    - Subsistence area: 150 < P < 3,500 mm and m > -6 °C and M < 45 °C.
    - Production area for 9 t.DM/ha/yr: 1,000 < P < 3,500 mm and m > 1°C and M < 36 °C.

- Genus *Pinus* (*P. radiata*, *P. Patula P. caribaea*, *P. keshiya P. massoniana*, *P. sylvestris*, *P. Taeda* & *P. elliotti*) where yields reach a sustainable 6 t.DM/ha/yr (Cab International, 2000; Kadeba, 1991; Chauvet, 1969):
    - Subsistence area: 200 < P < 5,000 mm and m > -40 °C and M < 45 °C.
    - Production area for 6 t.DM/ha/yr: 900 < P < 5,000 mm and m > -15 °C and M < 35 °C.

GIS based suitable soil and weather areas evaluation methodology

Bioclimatic envelopes suitable for plantation are generated in GIS. This software tool has made possible the storage, the management, the processing and the representation of geographical information. This information combines geometric data (location and form) and thematic data (temperatures, precipitations, soils…).

The information is stored and represented in a raster format. To reflect areas potentially available for energy plantations with a productivity of each species, the bioclimatic criterions (m, M and P) were combined by the mean of spatial union (figure 4). The fundamental principle for this union is to intersect the space studied in several spatial units, therefore to demarcate this space that matches specific criteria. These operations provide us new geometric information. The result is a global combination of the bioclimatic criteria retained for each species.

Finally, soil constraints which adversely affect biomass productivity of each species have been also considered. The Soil map produced by FAO-UNESCO[3] has been used to extract for each species the soils types regarded as an edaphic constraint for the growth of species selected. For example, soils types as black carbonate soils for *Eucalyptus* and compact clay soils, hydromorphic soils for *Pinus* genus were systematically eliminated from suitable areas for plantation.

Location of the production areas

To locate areas of potential production for the mentioned species, the existing land cover, the official access rules to land and the sylvicultural practices which can impact on land suitability have been taken into account. To identify areas not available for plantation a set of rules was defined:

[3] FAO-UNESCO, 2003. Map of World Soil Resources (1:25.000.000), Land and Water development division of FAO.

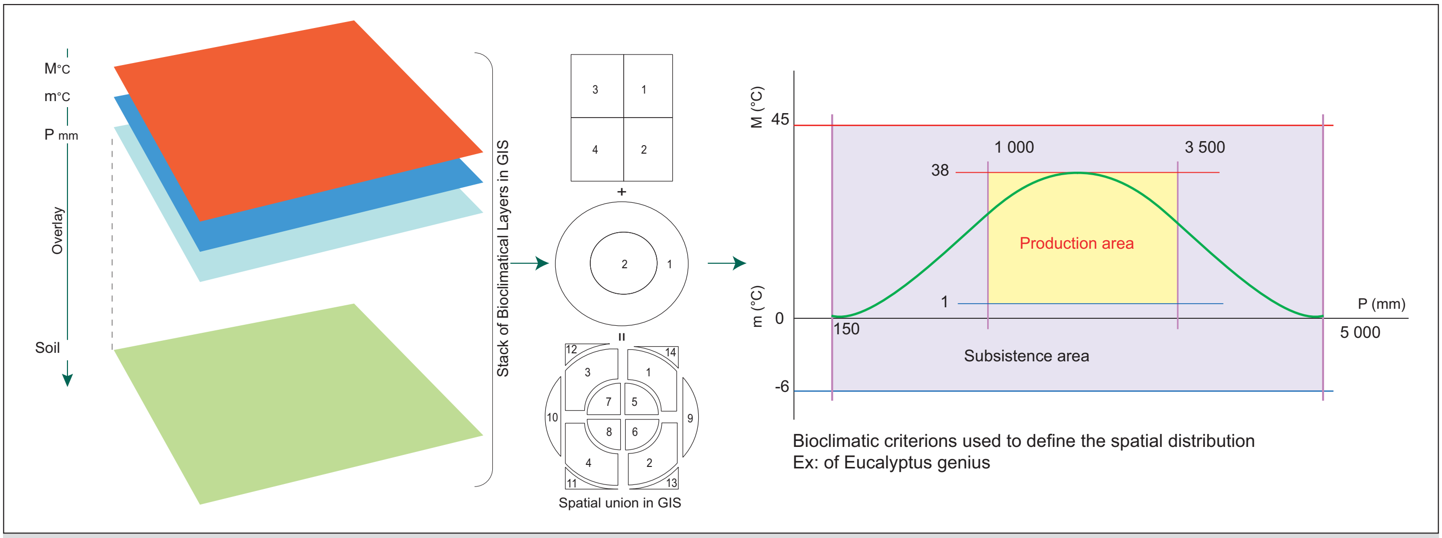

Figure 4.
Bioclimatic envelopes model in GIS.

- **Plantation is mechanized.** This assumption excludes all the surfaces with a slope of more than 12%. Identification and extraction of all surfaces that have a slope of more than 12% is performed by a spatial request on the Gtopo30 DEM.
- **No plantation in protected areas.** The WDPA[4] compiles information on protected areas at the worldwide scale. The construction and updating of this database to PNUS (United Nations Environment Program) is based on the input of information from multiple sources (research centres, ministries ...).
- **No plantation in natural forests.** The conversion of natural forests into wood plantations was not considered. Forest areas are extracted from Global Land Cover 2000 (Joint Research Centre, 2006).
- **No plantation in urban areas, lakes, water surfaces and bare soils.** The urban areas are extracted from Urban Expansion Model (UEM) for 2015 at worldwide scale (SEDAC-CIESIN)[5]. This model is based initially on the calculation of the average annual growth ratio[6]. To combine this estimate of the population change with the evolution of urban boundaries, the administrative boundaries of urban areas (polygons) were mapped by the use of satellite images based on the night lighting of urban areas. Thereafter, these polygons were assigned with their respective population data. For each city a 3 km buffer zone was allocated. If several cities are located inside the buffer zone, this buffer zone is aggregated with the initial administrative boundaries. However, for cities with difficult assignment buffer zones, a correlation between the size of the population of this city and its spatial spread is developed. This correlation is derived from a logarithmic regression allows a geographical extension depending on different parameters of development. Lakes, water surfaces and bares soils are extracted from Global Land Cover 2000 (Joint Research Centre)[7].
- **No plantation in cultivated areas.** In this assessment, for the sake of food security and in the logical of second generation biofuels, new energy plantations should not compete with existing crops, being mainly food crops. In spite of this simply and highly questionable assumption – many examples show that cash crops like cotton in Mali or sugar cane in South Africa, grown on good cropland, are not always in competition with food crops, but rather promote their expansion – and however, to more easily compare the results with those of existing studies, the assumption which considers that dedicated energy crops are not grown on existing croplands has been restraint.

[4] WDPA-UICN, PNUE, 2005. World Data base of Protected Areas. http://www.wdpa.org.
[5] SEDAC-CIESIN, 2004. Grided Population of the World and Global Rural -Urban Mapping Project. http://sedac.ciesin.columbia.edu/gpw.
[6] r=Ln(P2/P1)/(t1, t2) with P1 and P2 are the census of the population of the two years of references ; t1 and t2 are duration of growth of the two time reference periods. The extrapolation of the population for 2015 is estimated by the following formula: $P_{2015}=e^{rt}*P_1$, with r=average annual growth ratio; t=number of years over which the estimate is based and P_1 = population census of the first year of reference.
[7] JRC-IES European Comission Joint Research Centre-Institute for Environment and Sustainability, 2006. GLC-2000. http://ies.jrc.ec.europa.eu/global-land-cover-2000.
[8] See *nota bene*, p. 88.

Results

Geographic information system is used to evaluate the current biomass world potential of trees growth (*Acacia*, *Eucalyptus* and *Pinus*) based on georeferenced data inputs that include rainfall, temperatures and soil types.

The potential tree-planting areas of *Acacia*, *Eucalyptus* and *Pinus* are respectively about: 253 Mha for *Acacia*, 441 Mha for *Eucalyptus* and 560 Mha for *Pinus* (table II). The total of the areas available for plantations whose annual productivity sustainably reach 6-9 t.DM/ha are about: 600 Mha.

Genus *Acacia*[8]

Acacias are plants of vastly different sizes. Some of them are woody lianas, other are the low bushes, while others are large trees more than 35 meters (m) high. The tree adult canopy often characterizes the species. Many African acacias have a typical flat top, while most Australian species have a more or less spherical canopy.

The characteristics of the leaves and foliage acacias are diverse. Many African acacias trees tend to lose their leaves during the dry season, while most an Australian acacia have evergreen foliage. In South America there are species with deciduous and evergreen foliage (Ross, 1981). The leaves of some species have a more or less horizontal position, while phyllodes of many species of dry stations are vertical, which is probably an adaptation to avoid direct exposition to solar radiation. Natural regeneration is done primarily principally by reseeding, but some species can regenerate and expand through suckers or runners.

There are more than 1,200 species of Acacia. Their spatial distribution stretches to all the continents except Europe and Antarctica. At present there are 729 recognized species in Australia, and it is estimated that there are about 120 species have not yet been described. Africa possesses approximately 115 species (Ross, 1981), the rest being present in Asia (including China) and the Americas. In New Zealand, the genus is only known in a fossil state (Ross, 1981). An ecology acacia is presented by Pedley (1978) and Ross (1981).

The genus *Acacia* is a characteristic species of arid and semi-arid climatic regions, including Australia, where it is also common in many sub humid regions. It is less represented in humid region, and is rarely in the dense tropical forests or in the grasslands. Generally, the sub Africans acacias tolerate hot and arid climates, hot and humid, cold arid, but not cold and wet. However, in many areas of southeast Asia, *Acacia mangium* is located on humid dense forests which are being over logged or converted.

In arid zones, acacias colonize soils containing a high percentage of sand and gravel in their profile, such as dunes, sandy plains and rocky ridges, which form woodlands or "scrubs". In semi-arid zones, acacias expand on superficial soil with fine texture located on high ridges. An interesting feature of acacia trees is their ability to colonize land of low fertility, because of their capacity to fix atmospheric nitrogen with their symbiotic rhizobium association. The potential tree-planting areas of *Acacia* genus is shown in figure 5. The total of the areas available for plantations whose annual productivity sustainably reaches 9 t.DM/ha/year with 7 years rotation period is about: 253 Mha. This figure shows clearly that Brazil and Congo DRC hold the main available potential tree-planting areas.

Genus *Eucalyptus*

Eucalyptus is a genus whose introduction was a large success in many countries. There are some 800 different species of *Eucalyptus* with numerous hybrids (Maxwell, 1982). This success is due to their ability to grow rapidly under very diverse conditions of climate and soil.

The main factors that limit the spatial distribution of these species are low temperatures (m › -6 °C or m › 9 °C in Tasmania) and its inability to regenerate if soil moisture does not remain high for several months after seed germination. In contrast, soil conditions appear to impose a few limits to its spatial distribution. *Eucalyptus* grows on heavy clay soils or more generally on sandy soil deposits. In some regions, it tolerates calcareous shallow soils. Although soil moisture is an essential element in the first stage of seedling growth, *Eucalyptus* once well established is one of the most tolerant to drought. It can survive in areas where rainfall is very low and highly variable (ex.: *Eucalyptus camaldulensis*). These species is growing in a wide range of climatic conditions from tropical to the temperate climate. The main regions where it occurs (Australia) are characterized by 5 to 20 days of frost in the winter and high temperatures in summer. The temperature can vary from a minimum of -6 °C and a maximum of 50 °C. The diurnal amplitude reaches 21 °C. The annual precipitation is typically between 250 and 650 mm, but it may reach 1,000 mm or more in some few areas (Maxwell, 1982; Aciar, 1986). Its establishment in equatorial stations with large rainfall amount provides a rapid growth in very favourable conditions. The Potential tree-planting areas of *Eucalyptus* genus which annual productivity sustainably reaches 9 t.DM/ha/year is shown in figure 6. It is bout 441 t.DM/ha/year with 7 years rotation period. Once again, the figure shown clearly that Brazil and Congo DRC hold the main available potential tree-planting areas, mainly in subtropical zones for Brazil.

Genus *Pinus*[9]

From the taxonomic information, pines are divided into 2 or 3 sub-genus. The two sub-genera universally recognized are *Pinus* and *Strobus*. One to several species of sub-genus *Strobus* are sometimes separated in a third sub-genus: *Ducampopinus*. Each sub-genus may be divided into sections and subsections (Huxley *et al*., 1992). The three sub-genus are as follows:

- *Pinus* "hard-pines" or typical pines; about 73 species; scales of the cone to dorsal umbilicus with sealing tape; wing little or no adherent to the seed; leaves by 2 to 6, with stomata divided more or less evenly on all sides; sheath generally persistent.
- *Ducampopinus* "pine-nut"; about 20 species; scales of cones to dorsal umbilicus and without sealing tape wing not adhering to the seed; leaves by 1 to 5; stomata unevenly distributed, especially on the inside; seed lapsed or persistent.
- *Strobus* "soft-pines or white-pines"; about 23 species; cone scales to terminal umbilicus without sealing tape, wing strongly adhering to the seed; leaves by group of 5; stomata divided on all sides and especially on the inside, rarely evenly; seed lapses.

Mexico and Guatemala have most of the *Pinus* species in the world (Mirov, Larsen, 1958), in the mountainous western Guatemala only; nine species of pines have been observed.

Generally, pines tolerate dry summer, snowy winter, and strong temperature and precipitation variability. They often prefer dolomitic soils, with a few exceptions. In some parts of mountainous areas, some populations are growing on soils derived from Calcareous and gypsum. Some pines adapt to a large edaphic range and can grow in different soils.

The Potential tree-planting areas of *Pinus* genus which annual productivity sustainably reaches 6 t.DM/ha/year is shown in figure 7. It is bout 560 t.DM/ha/year with 14 years rotation period. The figure shown clearly that Brazil and China hold the main available potential tree-planting areas, mainly in subtropical zones for China.

Discussion

Many species and clones of genera *Eucalyptus* (*E. Grandis*, *E. urophylla*, *E. globules*, *E. gundal*, *Eucalyptus* spp.), *Acacias* (*A. mangium*, *A. auriculiformis*) and *Pinus* (*P. radiata*, *P. Patula* *P. caribaea*, *P. keshiya* *P. massoniana*, *P. sylvestris*, *P. Taeda* and *P. elliotti)* have rapid growth, produce good fiber, survive with limited damage and provide high yields on short rotations.

This analysis indicates that potential tree-planting areas of *Acacia*, *Eucalyptus* and *Pinus* genus based on a spatial distribution of bioclimatic envelopes, are respectively about: 253 million hectares (Mha) for *Acacia*, 441 Mha for *Eucalyptus* and 560 Mha for *Pinus*. The total of the areas available for plantations whose annual productivity (woody biomass) sustainably reaches 6-9 tons of dry matter per hectare and per year (t.DM/ha/year) is about: 600 Mha. These results are comparable with those of Copernicus Institute which give an estimation of 430-580 Mha (Hoogwijk *et al*., 2005).

As illustrated in figure 5, Latin American and African countries have the greatest potential for *Eucalyptus* tree-planting with respectively 176 Mha (spread over fourteen countries) and 128 Mha (spread over twenty-one countries). These two regions combine many favourable assets such as: low population densities; natural spaces like savannas and other arid environments which are still under-exploited and climate conducive to high productivity.

However, large uncertainties remain regarding the surfaces actually available to carry these new plantations and in particular on current agricultural lands. These uncertainties are related to the spatial resolution and lack of knowledge of land use[10].

The analysis is based on the use of existing databases with a spatial resolution of 1 km. In the agriculture-savannas environments as in Sub-Saharan Africa and in a large part of Brazil, lower resolution, increases the error of appreciation.

[9] See *nota bene*, p. 88.
[10] Land use class is a generalized land use description, defined by diagnostic criteria that pertain to land use purpose(s) and operation sequence followed; it has no location or time indication (De Bie, 2000). Conversely, Land cover is defined by the FAO (1998) as "the observed biophysical cover on the earth's surface".

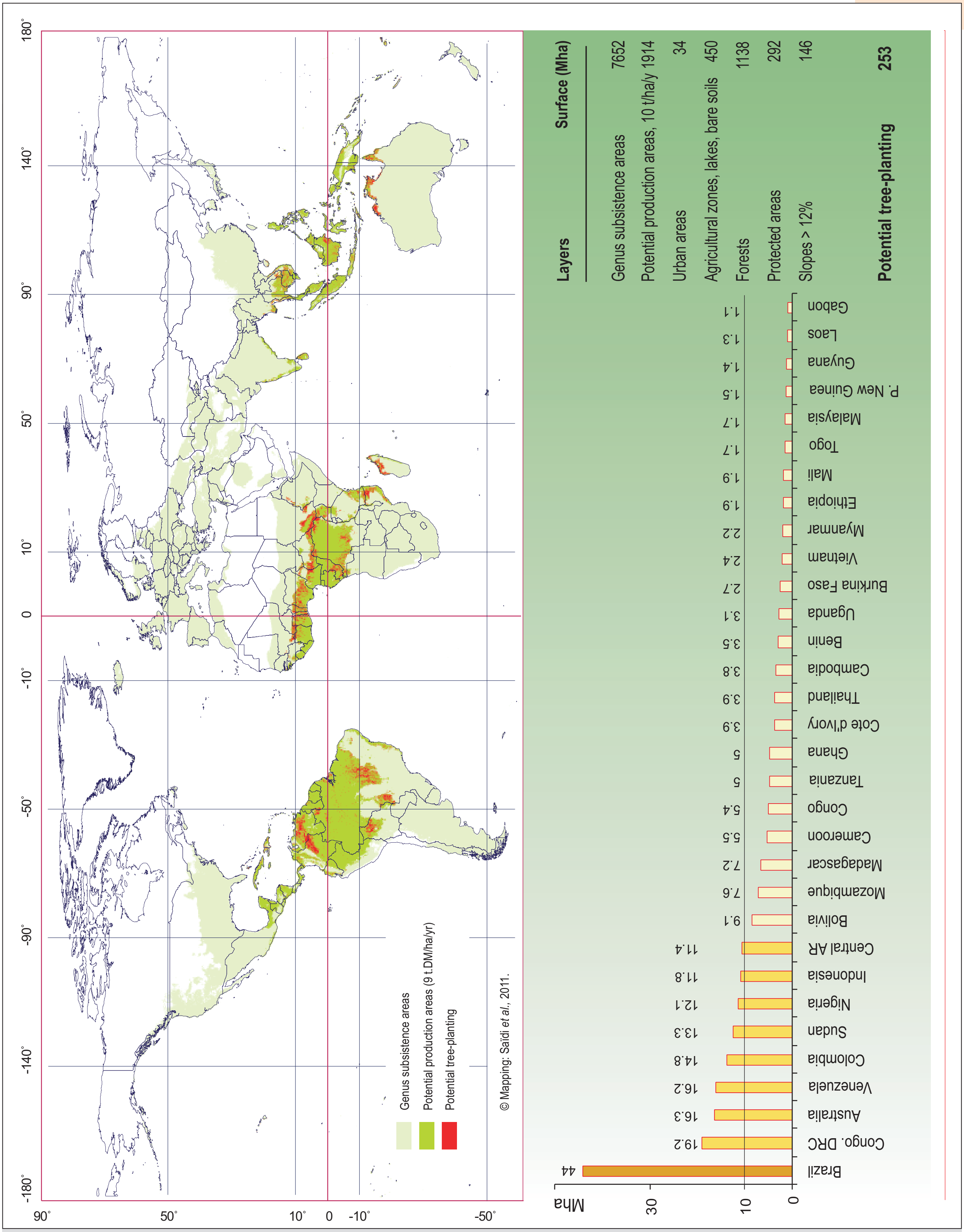

Figure 5.
Locating potential tree-planting sites of *Acacia* genus. © Mapping: Saïdi *et al.*, 2011.

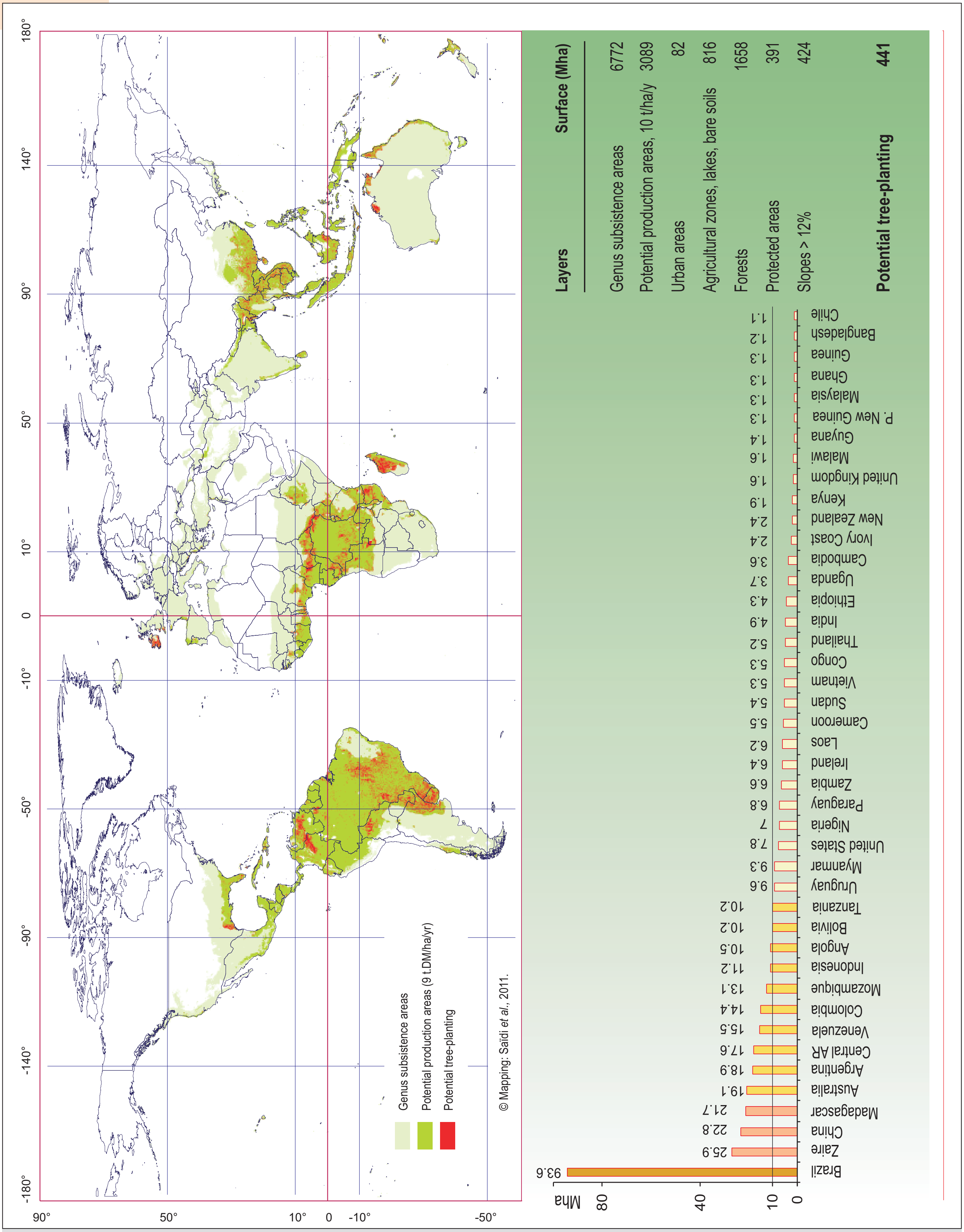

Figure 6.
Locating potential tree-planting sites of *Eucalyptus* genus. © Mapping: Saïdi *et al.*, 2011.

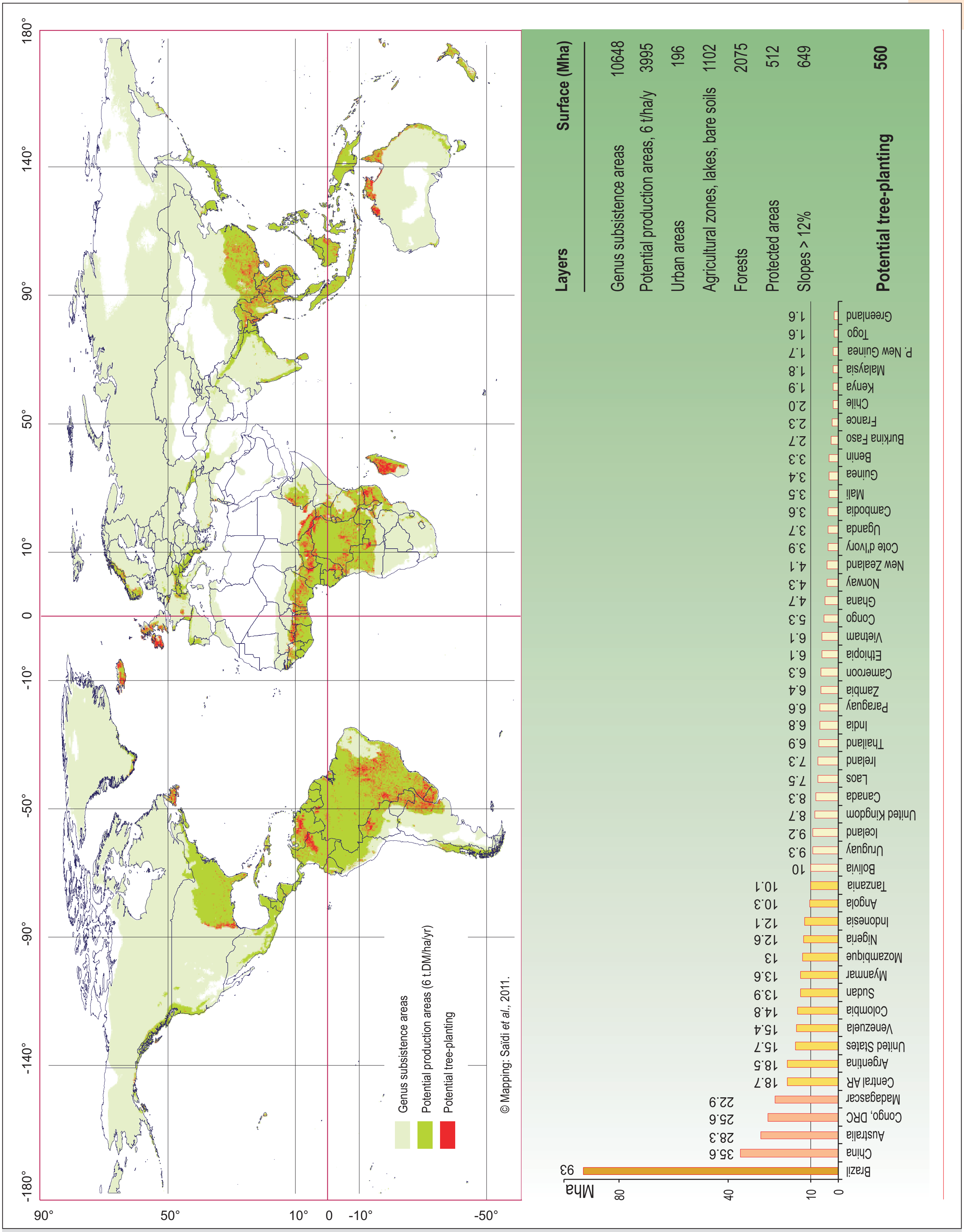

Figure 7.
Locating potential tree-planting sites of *Pinus* genus. © Mapping: Saïdi *et al.*, 2011.

This error is at the expense of cultivated areas which are characterized by small crops, whose detection is often difficult in savanna environments. Gazull (2007) indicates that in Mali, this kind of error generates an under-estimation of cultivated areas which is five times greater between GLC 2000 database and the local maps. For Brazil, Piketty *et al*. (2009) find that the total area of land potentially available is reduced by more than 40% when more accurate data that the global WDPA are used on protected areas.

Currently, all the studies about plantation potential assessment are based on land cover databases and not on land use databases. But, only land use categories can be used to evaluate the availability of lands. For example, in Africa as in Brazil, grasslands and shrublands are usually areas for cattle grazing. Thus, an ungrazed savanna can reasonably be regarded as an available land for plantation; while a grazed savanna should be considered as a pasture land and finally will be not available for energy crops: extensive livestock production system is based on this type of vegetation cover.

Many authors have indicated the importance of errors made on the estimation of savanna areas, particularly in Africa (Hannerz *et al*., 2008). Fao recognized that the current land cover databases were inadequate to carry out a realistic assessment of land development (George, Nachtergaele, 2000).

The limit of land cover database affects the validity of this study results and further studies are needed to refine estimations with a mix between land use and land cover categories. However, the bioclimatic envelopes approach can provide useful results, giving a first approximation for land productivity assessment. This study is intended to serve as a guide for identifying areas that require further attention and detailed analysis for biomass production.

Nota bene

A long list of bibliographical references was used to prepare this article. *Bois et forêts des tropiques Journal* can't publish all references. Therefore, it is possible to access to this references by contacting the authors.

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Pinus kesiya à Madagascar.
Photo D. Louppe.