Mapping vulnerability of tropical forest to conversion, and resulting potential CO_2 emissions

A rapid assessment for the Eliasch Review

UNEP WCMC

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Summary

Using global scale maps and statistics, we estimate that the conversion of all vulnerable tropical forests to the most valuable other land use at each location could lead to emissions of 670 Gt carbon dioxide (CO_2).

This analysis involved:

a) Estimating the theoretical maximum area that could be converted to different land uses: pasture, rainfed crops (oil palm, cane sugar, grain maize, soybean, rice) and logging by comparing the current distribution of tropical forest with estimates of land suitability for the different uses.
b) Identifying the most valuable potential land use at each location based on estimates and assumptions about potential income from each use.
c) Calculating the potential CO_2 emissions from the difference between carbon stocks in the original land cover and in the most valuable potential land use at each location.

We then evaluate the role of the global protected area network in preventing emissions from tropical deforestation. If all tropical protected areas were successful in meeting their objectives of preventing land use change, we estimate that they would contribute a 28% reduction in the total potential emissions from the conversion of vulnerable tropical forest. Recent research indicates that whilst protected areas are successful in reducing deforestation, they do not prevent it entirely (Clark *et al.* 2008). Strengthening the global protected area network could therefore make an effective contribution to reducing emissions from deforestation and forest degradation.

This is a rapid assessment analysis undertaken to inform the UK's Eliasch review on the role of international finance mechanisms to preserve global forests in tackling climate change. The results should be used with an understanding of the caveats specified at the end of the report.

Introduction

Approximately 13 million hectares of forest land globally are converted to other land uses each year (FAO 2005). Most of this loss, nearly 10 million ha, is from tropical forest (Fig 1; FAO 2007). The greatest annual losses are in tropical Africa and Latin America, with smaller but significant losses in tropical Asia. Tropical forests store more than 320 billion tonnes of carbon (Gibbs *et al.* 2007), and clearing these forests results in large emissions of carbon dioxide (CO_2) to the atmosphere; the annual emissions from current tropical deforestation have been estimated at ~1 – 2 $PgCy^{-1}$ (Ramankutty *et al.* 2007), 18-25% of global annual CO_2 equivalent emissions.

The principal reasons for tropical deforestation are conversion to cropland and pasture at both small and large scales (Geist & Lambin 2002, Lambin *et al.* 2001). Timber extraction is also an important factor in tropical forest degradation, though in itself it rarely involves complete removal of forest cover. However, by creating infrastructure such as roads, logging provides access for other conversion activities that often result in deforestation (e.g. Asner *et al.* 2006).

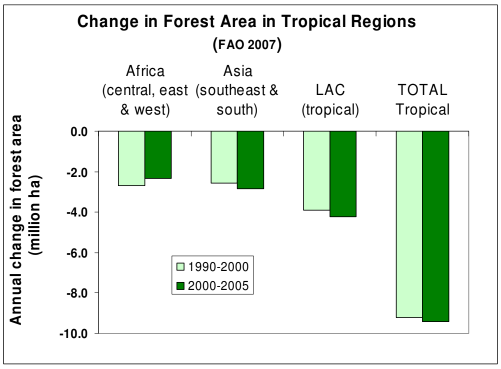


Figure 1: Annual change in forest area in tropical countries over the two periods covered by FAO's most recent forest resource assessments.

The causes of deforestation vary across the tropics and have changed through time. (Rudel 2005). In the 1970s and 1980s, the principal drivers of deforestation in most regions were government-driven settlement and infrastructure programmes and associated small-scale agriculture. During the 1990s, however, the deforestation became increasingly enterprise-driven as development of large scale agriculture dominated, particularly in Southeast Asia and Latin America (Rudel 2007). This reflects the greater influence of increasing prices for agricultural commodities and newly emerging markets, including most recently for biofuels. Logging pressures have also increased with globalisation and expansion of timber markets (Sohngen 1997), with the growing market for certified timber having a positive, but as yet limited, effect on the sustainability of the industry.

World trade in all agricultural commodities is projected to continue growing (OECD, FAO 2007), with the greatest growth for vegetable oils (70% by 2016) and for beef, pigmeat and whole milk powder (50% by 2016). World markets for cereals, sugar and, increasingly, oilseeds and palm oil, are strongly influenced by developments in biofuels. The commodities with the greatest projected growth in production in non-OECD countries are vegetable oils, oilseeds, and oilseed meals (projected annual growth 2.8, 2.6% and 2.5% respectively). Beef (2.4%) and sugar (2.2%) are also projected to show important increases in production outside OECD countries (OECD, FAO 2007). This growth in production may come in part from increasing yields but will also depend on increased area of production. Therefore, the most likely conversions of tropical forests will be for the cultivation of soybean, oil palm, sugarcane, maize and rice and for pastureland for beef production.

Soybeans are grown principally for oil production and animal feed. The area under soy cultivation has expanded dramatically in recent years, especially in Latin America, driven by growing demand for animal feed in China, coupled with a developing interest in soy-based biodiesel (Nepstad *et al.* 2006). In 2006, developing countries grew over 60 million ha of soybeans (FAOSTAT 2008). Increasing world livestock production will continue to drive the consumption of oilseed-derived protein meal (principally soy); oilseed meal consumption in the non-OECD region will swell by over 55% with over two-thirds of that growth attributed to Brazil and China alone (OECD, FAO 2007). Developing interest in biodiesel production will further bolster the demand for oilseeds in the EU and elsewhere (OECD, FAO 2007).

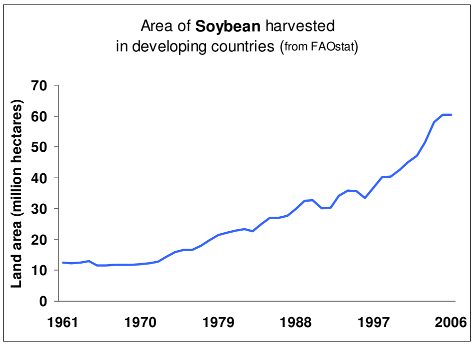


Figure 2: Trend in soybean cultivation in developing countries

Recently soybean production has become one of the most important contributors to deforestation in the Brazilian Amazon (Cerri *et al.* 2007). Previously, new soy cultivation was concentrated mainly on the periphery of the Amazon basin, where the soils are richer than in the main part of the basin. However, rising demand and new cultivars suited to the Amazon climate, have enabled the rapid northward expansion of soy well beyond the areas historically used for its cultivation (Fearnside 2001, Nepstad *et al.* 2006, Cerri *et al.* 2007). Oilseed production in Brazil and Argentina will continue to intensify as arable land is diverted from pasture to oilseed crops. With its production projected to grow by 3.9% per year on average between 2007 and 20016, Brazil will by 2009 be the world's largest oilseed exporter (OECD, FAO 2007). It has been estimated that by 2015, approximately 60% of the newly deforested area in the Brazilian Amazon will be used for soybean cultivation (Cerri *et al.* 2007), though much of that land will first have passed through a phase of use as cattle pasture (Morton *et al.* 2006).

Oil palm plantations produce palm oil, used in a wide range of food products and for many other industrial products. Oil palm is a rain forest tree native to West Africa and is ideally suited for growth in many tropical rainforest locations. It is grown throughout the tropics, with the largest extent and production in Africa and Asia, where plantations are frequently established by clearing rain forest land. In 2006, there were over 13 million ha of oil palm plantations globally (FAOSTAT

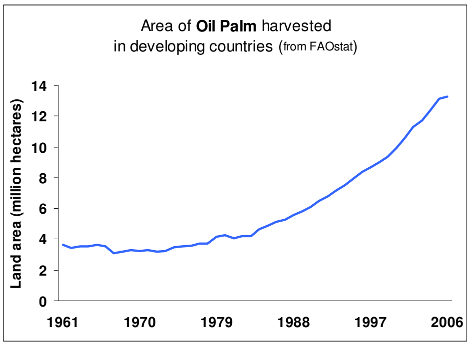


Figure 3: Trend in oil palm cultivation in developing countries

2008), of which the vast majority are in Indonesia. The global production of palm oil was over 37 million tonnes in 2006/07 (USDA 2008), of which the vast majority (nearly 32 million tonnes) came from Indonesia and Malaysia.

The demand for palm oil is growing rapidly both for food and industrial use, including as a substitute for European rapeseed oil now increasingly used for biodiesel rather than in foods, and as a feedstock itself for biodiesel (Casson 1999). Consumption is growing faster for vegetable oils, both from oilseed crops and from palm, than for any other commodity and will continue to do so (OECD, FAO 2007). This growth is driving rapid expansion of oil palm plantations; the total oil palm area in Indonesia expanded by more than an order of magnitude between 1967 and 2000, from less than 2000 km^2 to over 30,000 km^2 (FWI/GFW 2002), with much of this area derived from deforestation. Palm oil plantations are also expanding in Africa and Latin America (FAOSTAT 2008).

Sugar cane has long been cultivated in the coastal humid and seasonal tropics to produce sugar for domestic and industrial use. In recent decades, production has increased to support a growing industry producing ethanol for use as fuel, especially in Brazil. In 2006, sugar cane was grown on 20.4 million hectares worldwide, producing over 1.3 billion tonnes (FAOSTAT 2008). Ethanol production in Brazil is expected to continue growing at increased rates, and to reach some 44 billion litres by 2016, representing an increase in sugar cane use of 120% over ten years (OECD, FAO 2007). Further production and trade growth is also expected in other leading sugar exporting countries, such as Australia and Thailand.

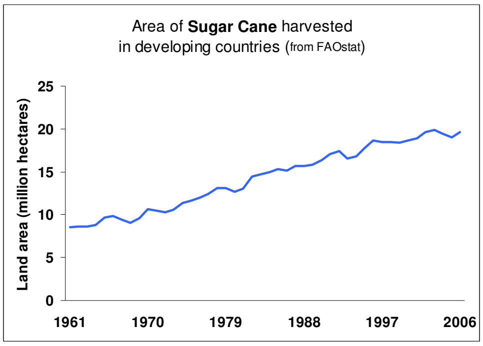


Figure 4: Trend in sugar cane cultivation in developing countries

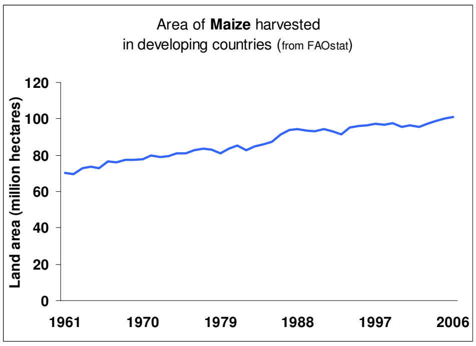


Figure 5: Trend in maize cultivation in developing countries

Like sugarcane, maize is a C4 grass that is highly productive at low latitudes as long as soil nutrients and water supplies are adequate. Developing countries grew over 100 million ha of maize in 2006 (FAOSTAT 2008). Maize is a staple food crop throughout much of the tropics. Development of new cultivars has increased the potential for enterprise-scale agricultural production of maize in the tropics.

The unprecedented demand for maize coming from rapidly growing biofuel production in the United States is transforming the coarse grain market. Driven by current low stocks and high prices there will be a shift towards more area planted in cereals, either from reallocation of land from other crops and set aside by OECD producers or from cultivation of new land in many developing countries, particularly in South and Latin America (OECD, FA0 2007).

Rice is a staple food crop of growing importance at global scale, and an essential crop for many developing countries. In 2006, these countries grew over 150 million ha of rice (FAOSTAT 2008). While most rice is produced in paddy agriculture, dryland or unirrigated rice is increasingly important, especially in Latin America and Africa, as nations seek greater self-sufficiency. In 2001, rainfed and upland rice were grown on over 3.7 million ha in Latin America and over 4.5 million ha in Africa (IRRI 2008).

Growth in rice consumption remains tied to underlying population growth. Rice production will likely expand due to national and regional efforts promoting rice cultivation as a means of supporting farmer incomes, encouraging food self-sufficiency and limiting rural emigration, especially in parts of Sub-

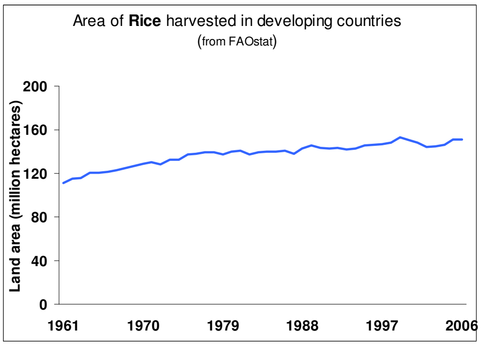


Figure 6: Trend in rice cultivation in developing countries

Saharan Africa and other developing countries. However, the largest production gains in the next decade will come from the major rice producers, such as India, Indonesia, Thailand and Viet Nam (OECD & FAO 2007).

Globally, meat production and consumption have been increasing steadily, and are projected to continue to do so, especially in developing countries (OECD, FAO 2007). With disease and other crises affecting major centres of production in temperate latitudes, the production of beef from tropical lands has become increasingly profitable (Nepstad *et al.* 2006). In 2006, developing countries produced over 167 million tonnes of meat, up from 137 million tonnes in 2001 (FAOSTAT 2008).

Pasture expansion is a major cause of deforestation (Chomitz *et al.* 2006, Steinfeld *et al.* 2006), especially in Latin America, where it has been the most important cause of forest loss over the last decade (Kaimowitz *et al.* 2004, Laurance *et al.* 2004, Nepstad *et al.* 2006, Soares-Filho *et al.* 2006, Nepstad *et al.* 2008). According to simulations by Cerri *et al.* (2007), pasture will be established on 40% of newly cleared area in Latin America by 2015. By 2016, Brazil is expected to provide 28% of total world meat exports (OECD, FAO 2007).

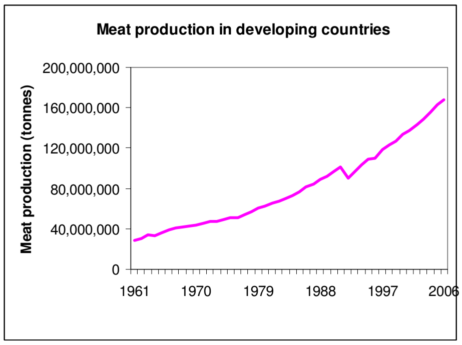


Figure 7: Trend in meat production in developing countries

Pasture establishment can produce at least some short-term financial gain from even the most marginal lands. Conversion of tropical forest to pasture land requires fewer inputs than any of the agricultural uses described above. It usually involves felling of the forest, with or without the removal of timber, followed by burning of the residues. Pasture is usually established using broadcast seeding, and there is no tillage or other treatment involved. Maintenance of pastures typically requires repeated burning to control weeds and produce fresh flushes of grass growth for cattle.

Coffee and cocoa are also economically important crops in the tropics but the scale of conversion for these uses is more difficult to quantify, in part because they are typically grown in agroforestry systems. Few other crops are expected to play a major future role in large-scale conversion of tropical rain forests. Only banana/plantain, sweet potato and cassava have any significant suitability in the core rain forest regions, while groundnut and millet are also important. These and many of the other crops for which tropical lands are suitable play a more significant role in subsistence farming and/or are of lesser economic importance in large-scale agriculture. The development of subsistence farming tends to be driven by access and ownership issues rather than crop suitability *per se*. Lands in the seasonal tropics are suitable for crops such as millet, sorghum, groundnut and cotton, but on the whole these are less important economically than soybean, oil palm, sugar, maize and rice. We therefore focus in the present analysis on these five major tropical crops.

The global market for timber has increased steadily since with global consumption of industrial roundwood exceeding 1.6 billiom m^3 in 2004 (FAO 2007). Tropical timber production supplies a significant proportion of this demand; production of tropical industrial roundwood (logs) in ITTO producer countries was forecast to total 138.8 million m^3 in 2007 (ITTO 2006). As stocks of high value species are depleted, prices of tropical hardwoods in particular continue to rise, placing additional pressures on resources. Recent reports have suggested that selective logging may degrade as large an area of forest as is converted to other land uses on an annual basis (Nepstad *et al*. 1999) and is increasing in frequency and extent (Asner *et al*. 2005). Logging can include small-scale tree felling for subsistence use, reduced impact logging, or conventional selective logging, which leaves the forest standing but makes no attempt to reduce damage (Feldspauch *et al*. 2005). For example, Nepstad *et al.* (2008) produced a map of projected forest cover change in Amazonia by 2030 based on 'business as usual' deforestation patterns, climatic conditions, and an expansion of logging as estimated by a rent-based economic model (Merry *et al*., in press). It was estimated that 31% of closed canopy cover in the Amazon basin would be lost through deforestation and 24% damaged by drought or logging, the incidence of which is higher along forest edges (Nepstad *et al*. 2008). Further, more than 30% of the relatively pristine forests in Central Africa are under logging concessions (Laporte *et al*. 2007). Logging is also often a precursor to other types of land conversion, especially because it tends to increase accessibility for agricultural development (Chomitz *et al.* 2006).

All of these changing land uses potentially release significant amounts of carbon to the atmosphere and therefore contribute to global climate change (Houghton 1999). The potential for emissions of carbon from standing biomass removed in forest clearance is obvious, although the land uses discussed above vary in the degree to which the biomass of the land use itself may replace some of that carbon. What may be less obvious is that conversion from tropical forest to agriculture has implications for carbon stored in soil. Although conversion often leads to decrease in soil carbon, such changes are extremely variable and depend upon the crop type, the management of the land post-conversion, and the year and depth of sampling (Murty *et al*. 2002). The purpose of the current study is to provide a conceptual overview of the potential for carbon emissions from conversion of tropical forest to other land uses by mapping suitability for different uses and calculating the emissions likely to result from total conversion of suitable areas.

Method

This review estimates the theoretical maximum area that could be converted to different land uses and the resulting carbon emissions. The land uses considered are pasture, rainfed crops (oil palm, cane sugar, grain maize, soybean, rice) and logging.

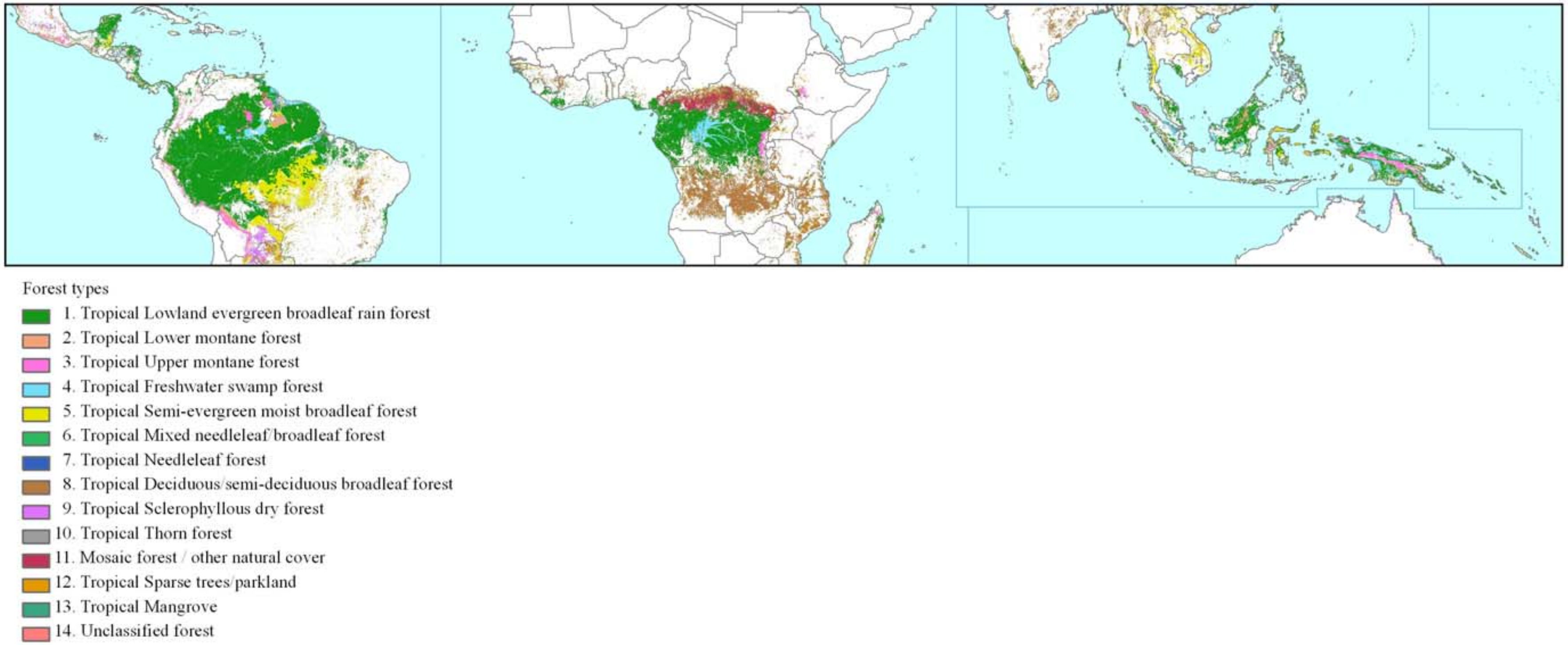
To estimate the theoretical area that could be affected by each major type of tropical forest conversion, the current distribution of tropical forests is compared with estimates of land use suitability. The potential carbon emissions are then calculated based on the difference between carbon stocks in the original land cover and in the newly converted land cover. Thus, the estimates use a "committed flux" approach that assumes all biomass carbon will eventually be emitted to the atmosphere as CO_2 over the long term, rather than an "annual balance" approach that would model cumulative emissions over time (Fearnside 1997, Ramankutty *et al.* 2007).

Tropical forest cover

The forest cover distribution is derived from remotely sensed data for 2005 acquired by the MODIS sensor and processed by the University of Maryland to provide estimated tree cover globally with a spatial resolution of 500 m (Hansen *et al.* 2006). The MODIS data represent percentage canopy cover. There is a tendency to over-estimate forest cover and to include some non forest areas such as woody shrubland as tree cover, and this tendency is more pronounced for the lower classes of tree cover (Fritz & See 2008; Giri *et al.* 2005). Therefore, a minimum threshold of 30% tree cover was used to represent closed tropical forests.

The cover was adjusted using the Global Landcover 2000 dataset (Bartholome & Belward 2005), to reduce further the potential errors arising from false detection of tree cover. Thus, areas classed as >30% tree cover according to MODIS but not appearing in one of the GLC2000 forest cover classes were removed. This approach may exclude significant areas of regenerating forest (cleared prior to 2000 but regenerating by 2005), and thus provides a conservative estimate of the total extent of tropical forest that could be converted to different land uses. A total of > 14.4 million km^2 of tropical forest was identified in the resulting map.

The map of tropical forest extent was subsequently classified by overlaying UNEP-WCMC's Global Forest Map (Iremonger *et al*. 1997), which is based on harmonised data and forest classifications from a wide range of sources, including national and regional vegetation maps, and incorporates 1992-93 AVHRR data for some countries and regions. As the MODIS data are more detailed than the Global Forest Map, a few small areas of forest could not be classified using this overlay. The resulting classified map of global tropical forest with >= 30% tree cover is shown in Map 1, which also illustrates the summary regions used in the present analysis.



Map 1: Tropical forest coverage and types from 2008 revision of Global Forest Map, showing region boundaries used for analysis (Latin America, Africa, Asia and Australia/Oceania[1]).

[1]Hawaii is omitted from the map extent, and bundled with Australia for summary statistics

Land use suitability

Agricultural uses: The Global Agro-ecological Assessment (Fischer *et al.* 2001, 2002; van Velthuizen *et al*. 2007) provides a series of maps at 5' resolution detailing the suitability of land for numerous crops assuming different levels of farming technology and management. These maps are based on an analysis of crop yields in relation to climatic variables, soils and terrain. These variables were used by IIASA and FAO to generate, for each crop, each grid-cell and each of three management levels, a crop-specific suitability index under rain-fed and irrigated conditions. The management levels are (i) a high-input, mechanized system using high-yielding varieties; (ii) a traditional, low-input system with low-yielding varieties and no agrochemicals or mechanization, and (iii) an intermediate system employing some mechanization and agrochemicals. The suitability index (SI) reflects the composition of a particular grid-cell. In this index "VS" represents the portion of the grid-cell with attainable yields that are 80% or more of the maximum potential yield, whilst "S", "MS" and "mS" represent portions of the grid-cell with attainable yields 60%-80%, 40%-60%, and 20%-40% of the maximum potential yield, respectively.

For this analysis, we selected those maps corresponding to an approach that 'maximises the technological mix' for rain-fed agriculture: that is, it assumes that the higher levels of inputs will only be employed in areas producing higher yields under these farming systems. These maps for individual crops had been produced using the following approach to calculate sub-grid cell areas for input to the index: (i) all land very suitable and suitable at a high level of inputs was selected; (ii) Of the balance of land after (i), all land very suitable, suitable or moderately suitable at an intermediate level of inputs was selected; and (iii) of the balance of land after (i) and (ii), all suitable land (i.e. very suitable to marginally suitable) at a low level of inputs was selected. The index is then calculated using the total areas from (i) to (iii) above as: $SI = VS*0.9 + S*0.7 + MS*0.5 + mS*0.3$.

For the current analysis, it is assumed that only areas in the three highest suitability index classes (i.e. 'very high', 'high' and 'good' suitability; suitability index >55) are likely to be converted for large-scale agriculture. The maps in the Results section show the forest areas identified as vulnerable to conversion to pasture and for each crop (i.e. the selected suitability classes for forest only); and the emissions resulting from those conversions. In the Annex, Maps A1 to A5 show the original global suitability layers for each crop.

Pasture: FAO and IIASA have also jointly derived a map of land suitability for pasture using similar approaches (van Velthuizen *et al.* 2007). This focuses solely on rain-fed systems and low input systems, as irrigation and higher inputs are unlikely ever to be used for pasture production. As for the analysis of potential conversion to crops, we confined the analysis of potential conversion to pasture to areas of suitability index >55. Map A6 shows the global suitability layer for pasture.

Logging: There is no equivalent existing assessment for the suitability of tropical lands for logging. The factors that affect forest vulnerability to logging are complex and vary in space and time. They include the existence and density of trees of commercial interest as well as field conditions such as slope and soil conditions that make their extraction more or less feasible. Legal forest concessions will increase susceptibility to logging (Nepstad *et al.* 1999), but illegal logging is so commonplace (Saaki 2006) that even if a global layer of forest concessions were available, it would not suffice to define vulnerability. The degree to which physical barriers to logging do indeed inhibit it is highly variable and strongly affected by the market value of the timber concerned (Barreto *et al.* 2006, Sohngen *et al.* 1997). Indeed, it has been noted that forest loss in accessible areas is pushing logging into flooded, steep, and rocky lands (Putz *et al.* 2001). Nonetheless, various logging guidelines suggest that logging should not be carried out on slopes from 35-45% (FAO 1999, Elias *et al.* 2001, Gustafsson *et al.* 2007), and 30% is generally considered a reasonable slope maximum (Dykstra & Toupin 2001). A study by Yijun & Hussin (2003) for Southeast Asia found very few logging areas on steep slopes, suggesting that constraints on logging slopes greater than 40% in the region were well observed.

In theory, it would be useful to incorporate maps of the distribution and density of trees of commercial interest, but in practice, these maps have not been developed. Commercially valuable trees have frequently been logged over much of their natural range, so simple maps of extent would overestimate their influence on logging suitability (Prates-Clark *et al.* 2008, Verissimo *et al.* 1995)

The existence of road and river access is critically important to the economic feasibility of logging at any given point in time (Barros & Uhl 1995, Verissimo *et al.* 2000), but if the value of the timber is sufficient, roads may be constructed almost anywhere (Minnemeyer *et al.* 2002). Therefore in the present analysis, forest type has been used to indicate forests with at least some timber potential. It was assumed that all tropical forest types shown in Map 1 may contain useful timber except for: mangrove, thorn forest, sclerophyllous dry forest and upper montane forest, all of which are characterized by trees of low stature that are unlikely to be appropriate for use as timber; and for mosaic vegetation, which is likely to have little remaining commercially valuable timber, so would not be vulnerable to logging on a large scale. In some regions, such as Northern Sumatra, these forest types are in reality logged, so this is a conservative assumption. We then constrained areas to those vulnerable to logging using an estimation of slope (data from Fischer *et al*. 2002), eliminating areas of median slope >30% at a 5' resolution. Slope estimates at this relatively coarse resolution mask much on-the-ground variation in terrain. A 30% threshold, slightly lower than the 35 to 45% cited in logging guidelines, is therefore likely to be conservative in indicating areas less vulnerable to logging. The use of a median identifies areas of rugged landscape at a spatial scale equivalent to that used for the agricultural suitability layers, and captures steep slopes that are smoothed out at this resolution. Thus, areas vulnerable to logging are those that contain at least some trees usable for timber and that can at least potentially be accessed for logging operations. This approach is directly comparable to that taken for agriculture, but is an over-estimate of the area vulnerable to logging because it does not take explicit account of the economic constraints imposed by lack of road access. It also fails to take account of any attempts to make logging practice responsible through conservation of fragile soils or watersheds. On the other hand, this study does not address other extraction of wood from forests, such as for fuel or domestic construction, which is highly variable in intensity and dependent upon distance from human settlements and access routes.

Potential carbon emissions

Carbon Stocks

The biomass carbon stocks of natural ecosystems were estimated using the Intergovernmental Panel on Climate Change (IPCC) Tier-1 approach (Table 1) (IPCC 2006, Gibbs *et al*. 2007). First, IPCC default values for the humid, seasonal and dry ecoregions for each continents were used to estimate above ground biomass carbon stocks. Then, below-ground biomass were estimated using the IPCC root-to-shoot ratios by vegetation type and ecoregion (IPCC 2006). Lastly, biomass values were converted to carbon stocks using the carbon fraction for each vegetation type (0.47 for most forests). Time-averaged carbon stocks for cropping systems were estimated by assuming linear growth rates, and using half the peak carbon stock (van Noordwijk *et al*. 1997). A combined map of carbon storage in terrestrial ecosystems (Ruesch & Gibbs in review) was produced using these globally consistent estimates (Map A7). These data are the most recent available for global vegetation carbon, and the only global estimates to follow IPCC Good Practice Guidance for reporting greenhouse gas emissions.

Table 1: Estimates of carbon stocks for tropical landscapes (Gibbs *et al*. in review).

All values include carbon stored in aboveground and belowground living plant biomass (t C / ha)

Biomass Carbon of Tropical Land Cover Types (t C / ha)									
	Americas			Sub-Saharan Africa			Southeast Asia		
Crop Type	Humid	Seasonal	Dry	Humid	Seasonal	Dry	Humid	Seasonal	Dry
Forests	193	128	126	200	152	72	225	105	78
Disturbed Forest	97	64	63	100	76	36	113	53	39
Shrubland / Sava	64	43	42	67	51	24	75	35	26
Grassland	8	8	4	8	8	4	8	8	4
Degraded Land	1	1	1	1	1	1	1	1	1
Annual Cropland	6	7	7	4	3	5	5	5	5
Sugarcane	10	14	10	10	10	14	14	14	14
Oil Palm	71	81	69	17	24	53	88	78	82
Coconut	96	112	108	68	50	39	67	80	83

Soil carbon stocks are likely to decrease with conversion of natural ecosystems, and increase with conversion to agriculture of degraded lands (Murty *et al*. 2002). In most cases, changes in soil carbon will likely be small relative to changes in vegetation carbon stocks (Brown 2002), but significant emissions have been estimated from conversion of other ecosystems with a high organic matter content in the soil, such as peat swamp forests (e.g. Hooijer *et al*. 2006). An organic soil carbon dataset, published by the International Geosphere-Biosphere Programme in 1998, was therefore selected for use in this study (IGBP-DIS 2000). It estimates organic carbon density to 1 m depth, at 5 minute resolution, which is appropriate for estimate soil carbon emissions from land conversions in most cases, but probably underestimates carbon emissions from deeper peatland systems. No global dataset of peat depth is yet available.

A combined map was generated to allow analysis of biomass and carbon stocks (Map 2, below).

Carbon emissions

To estimate the maximum potential carbon emissions from complete conversion of all suitable forest area to each land use in turn, the difference was calculated between the carbon stocks of the tropical forest source and those of the converted cropland or pasture land use (Map 2, Table 2). This approach estimates the net committed carbon flux by assuming that all biomass carbon stored in the tropical land source will be emitted to the atmosphere as CO_2 over the long term (Fearnside 1997). For soil carbon, it is estimated that 25% is lost on conversion to agricultural systems, and 10% is lost on conversion to oil palm plantations. These figures are likely to underestimate the impacts of conversion on soil carbon in peatlands (Hooijer *et al*. 2006), and losses of soil carbon on logging and conversion to pasture are not estimated as a result of a lack of available data.

Estimating emissions from logging is more challenging because of the varying intensity of logging (<1 m^3ha^{-1} to >100 m^3ha^{-1} depending on region, forest type and logging system, with highest intensities in Asian Dipterocarp forests; Putz *et al.* 2001, Asner *et al*. 2005, Johns *et al*. 1996, Curran *et al*. 2004), the wide range of impacts from different logging systems (15-50 (-80)% canopy damage from selective logging; Pinard & Cropper 2000, Keller *et al*. 2004) and the dynamic nature of regenerating forests. Indeed, few studies on the overall damage caused by selective logging exist at a regional scale, let alone a global estimate. Available studies show that the harvesting process alone can damage or destroy up to 40% of biomass in the logging area (Nepstad *et al*. 1999, Uhl *et al*. 1991, Verissimo *et al.* 1992) without accounting for all residual damage (Osborne & Kiker 2005). As a first approximation, it is assumed here that a logged forest retains approximately half the biomass carbon of an intact forest (Houghton & Hackler 1999, Gibbs *et al*. 2007). This approach may over-estimate carbon loss from forests that recover rapidly, and from those with low logging intensity or reduced-impact logging techniques, but may underestimate cumulative secondary damage due to drought and fire (Gerwing 2002, Nepstad *et al.* 2008) and the eventual conversion of logged land to other land uses. In the Amazon, for example, a study has estimated that 16% of logged areas are fully deforested in the year following logging, while 32% of the area is subject to deforestation after a four year period (Asner *et al.* 2006).

Table 2: Remaining carbon stocks for modified tropical landscapes (adapted from Gibbs *et al.* in review).

Land use	Remaining stock in vegetation (tC)	Remaining stock in soil (% of original)
Oil palm	62	90%
Soybean	5	75%
Sugarcane	12	75%
Maize	5	75%
Rice	5	75%
Pasture	7	100%
Logging	50% of original	100%

Role of protected areas

To assess the potential importance of protected areas in reducing carbon emissions from conversion of tropical forest to other land uses, the analysis detailed above was repeated, but excluding all protected areas from agricultural conversion, and excluding from logging only those protected areas in IUCN categories I-IV as recorded in the World Database on Protected Areas (UNEP-WCMC & IUCN 2007). This estimates the role that a highly effective protected area network could play in emissions reduction. It does not address issues of 'leakage' of conversion pressure to zones outside protected areas.

Table 5 illustrates the substantial protective effect that the world's protected area network would have if fully effective.

Summary analyses

In addition to looking at the area under pressure from individual land uses, three summary analyses were carried out:

i) the number of different potential land uses for each area was examined (Table 6; Figure 8; Map 11). No area was vulnerable to all seven pressures; a large area is vulnerable to only one pressure, typically logging.

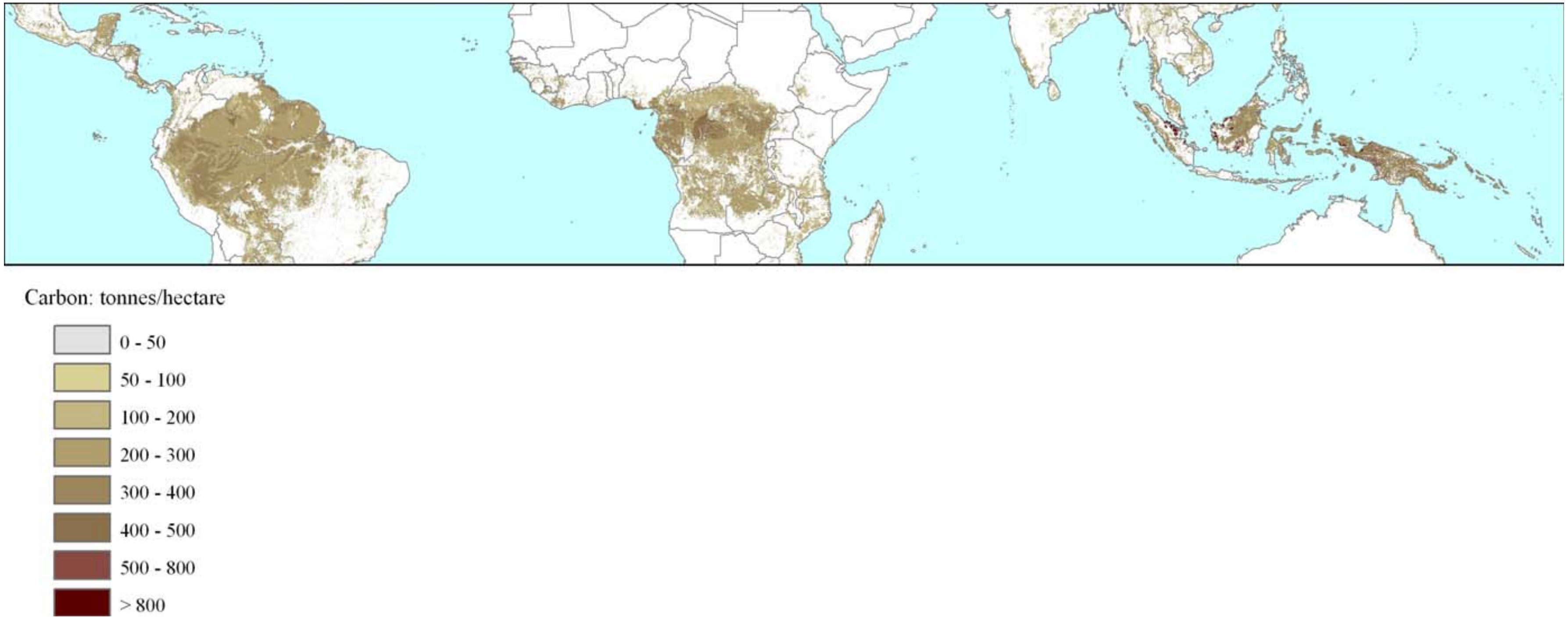
ii) the different potential land uses were ranked in order of their likely value (Table 3), informed by Grieg-Gran (2006). The value of agricultural land uses includes the value of any timber extraction during land clearing. It is clear that the precise land use selected in any location will be influenced by the likely costs, yields and market prices on a local scale and that these will vary through time.

Table 3: Ranking by value of different land uses

Relative value	Land use
High	Palm Oil
↓	Soybean
	Sugarcane
	Maize
	Rice
	Pasture
Low	Logging

The most valuable land use was then assigned to each forest area, and the forest area vulnerable to conversion to each use was estimated (Table 7; Figure 9; Map 12).

iii) the resulting carbon emissions from (ii) were estimated (Table 8; Figure 10; Map 13), with and without the influence of protected areas.



Map 2: Carbon stock density in tropical forest (above and below ground biomass plus soil carbon)

Results

Global summary

Table 4: Current tropical forest area, and total area vulnerable to conversion to different land uses (km^2)

	Africa	Americas	Asia	Australia, Oceania, Hawaii	Total
Current forest	4,727,747	7,258,832	2,369,135	71,720	14,427,434
Vulnerable to:					
Oil palm	793,175	2,436,954	183,213	15	3,413,357
Soybean	246,346	93,712	13,003	12,066	365,127
Sugarcane	899,127	681,584	24,489	121	1,605,321
Maize	275,761	128,620	19,556	13,392	437,329
Rice	1,053,440	1,374,566	41,825	1,690	2,471,521
Pasture	2,611,506	5,293,741	1,227,453	31,355	9,164,055
Logging	3,983,435	6,323,901	1,631,309	23,732	11,962,377

Table 5: Potential CO_2 emissions from conversion of all vulnerable tropical forest for each land use type, with and without the influence of protected areas

Land use	**Potential carbon dioxide emissions from conversion of all vulnerable tropical forest (Gt)**					**Potential carbon dioxide emissions from conversion of all vulnerable tropical forest (Gt) – excluding protected areas**				
	Africa	Americas	Asia	Australia, Oceania, Hawaii	Total	Africa	Americas	Asia	Australia, Oceania, Hawaii	Total
Oil palm	42.3	122.2	10.4	0.0	174.9	36.1	74.2	9.3	0.0	119.7
Soybean	13.4	4.7	0.5	0.6	19.1	10.4	4.1	0.4	0.4	15.3
Sugarcane	69.1	48.1	1.9	0.0	119.1	59.0	26.7	1.7	0.0	87.5
Maize	14.9	6.5	0.7	0.6	22.7	11.5	5.7	0.6	0.5	18.2
Rice	68.8	96.4	2.2	0.1	167.4	57.0	51.1	1.8	0.1	110.0
Pasture	159.3	329.8	82.7	1.9	573.7	133.1	187.7	70.1	1.6	392.5
Logging	122.9	203.5	52.0	0.8	379.2	115.7	181.0	47.6	0.6	344.9

Table 6: Tropical forest area vulnerable to conversion to multiple land uses (km^2)

Number of potential land uses	Africa	Americas	Asia	Australia, Oceania, Hawaii	Total
0	297,071	644,519	618,436	25,313	1,585,339
1	1,616,068	953,888	595,600	19,190	3,184,746
2	1,260,482	2,576,470	941,431	21,251	4,799,634
3	662,081	2,320,305	198,065	3,953	3,184,404
4	726,366	569,930	15,283	2,149	1,313,728
5	166,117	198,054	1,808	87	366,066
6	912	443	16	0	1,371

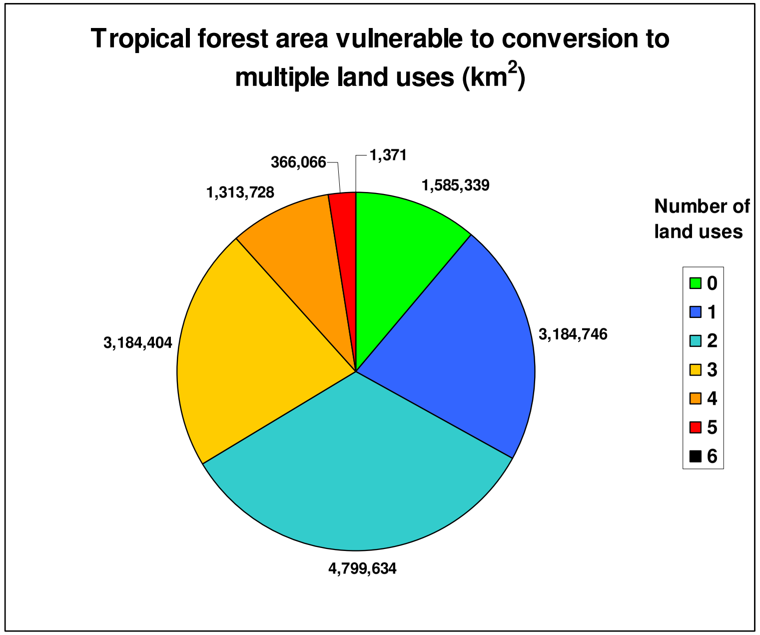


Figure 8: The area of tropical forest vulnerable to conversion to multiple land uses according to analyses using suitability maps. As the suitability criteria used are quite conservative, it is likely that some of the area classed as vulnerable to no land use conversions would in fact be vulnerable, while in other areas, access and other constraints

might mean that some conversions are highly unlikely. Most of the area where vulnerability is to a single land use is vulnerable to logging, with a small amount of the total vulnerable only to conversion to pasture.

Table 7: Tropical forest area vulnerable to conversion to each land use, when that use has the greatest potential economic value (km^2)

Most valuable use:	Value rank assigned (1 high)	Africa	Americas	Asia	Australia, Oceania, Hawaii	Total
Oil palm	1	793,175	2,436,954	183,213	15	3,413,357
Soybean	2	246,346	93,712	13,003	12,066	365,127
Sugarcane	3	241,404	206,209	10,833	110	458,556
Maize	4	52,274	34,911	6,824	1,489	95,498
Rice	5	635,494	884,998	37,099	293	1,557,884
Pasture	6	1,097,693	2,206,666	1,019,284	26,216	4,349,859
Logging	7	1,364,656	752,101	480,849	6,306	2,603,912
None	8	296,705	643,281	618,030	25,225	1,583,241

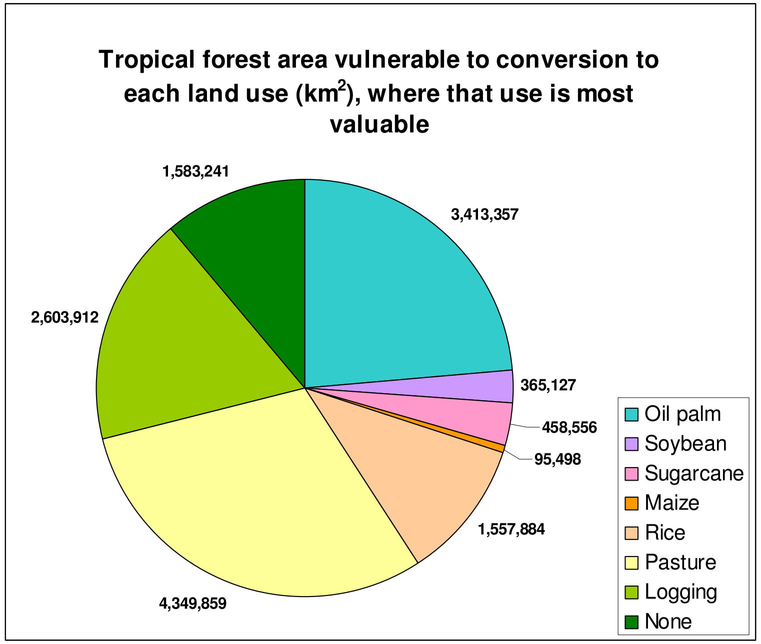


Figure 9: The total area of tropical forest vulnerable to conversion to each of the land uses, where that use has the greatest potential economic value. In reality, vulnerability to each type of conversion is influenced by regional customs and constraints, and some of the area shown here not to be vulnerable is likely to be converted for non-commercial production or for other uses. The proportion vulnerable to soybean cultivation is likely to be an underestimate, as new GMO varieties have been introduced that are more suitable for production in tropical forest zones.

Table 8: Potential CO_2 emissions from conversion of all vulnerable tropical forest to most valuable potential land use, with and without the influence of protected areas (km^2)

Land use	Potential CO_2 emissions from conversion of all vulnerable tropical forest to most valuable land use (Gt)					Potential CO_2 emissions from conversion of all vulnerable tropical forest to most valuable land use (Gt) – excluding protected areas				
	Africa	Americas	Asia	Australia, Oceania, Hawaii	Total	Africa	Americas	Asia	Australia, Oceania, Hawaii	Total
Oil palm	42.3	122.2	10.4	0.0	174.9	36.1	74.2	9.3	0.0	119.7
Soybean	13.4	4.7	0.5	0.6	19.1	10.4	4.1	0.4	0.4	15.3
Sugarcane	17.5	13.9	0.9	0.0	32.2	15.0	7.6	0.8	0.0	23.4
Maize	2.8	1.7	0.3	0.1	4.8	2.2	1.6	0.2	0.1	4.1
Rice	40.2	61.8	1.9	0.0	103.9	33.7	33.7	1.5	0.0	69.0
Pasture	64.7	131.2	68.4	1.7	266.1	54.0	71.5	57.4	1.4	184.2
Logging	36.7	20.5	11.6	0.2	68.9	35.3	18.7	10.1	0.1	64.2
None	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	217.6	356.0	93.9	2.5	670.0	186.7	211.4	79.8	2.0	479.9

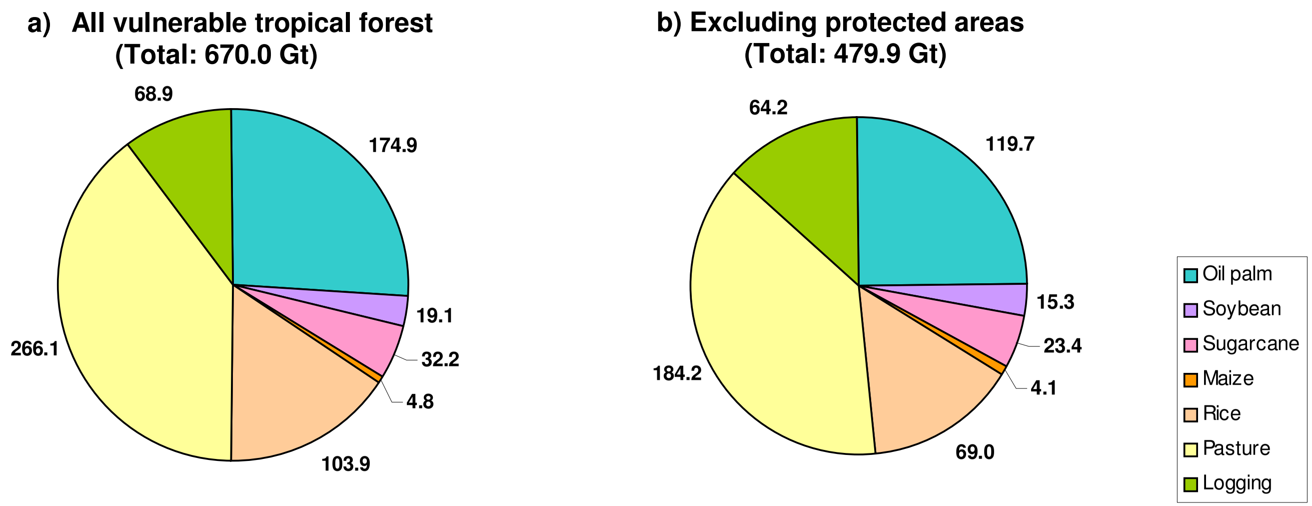
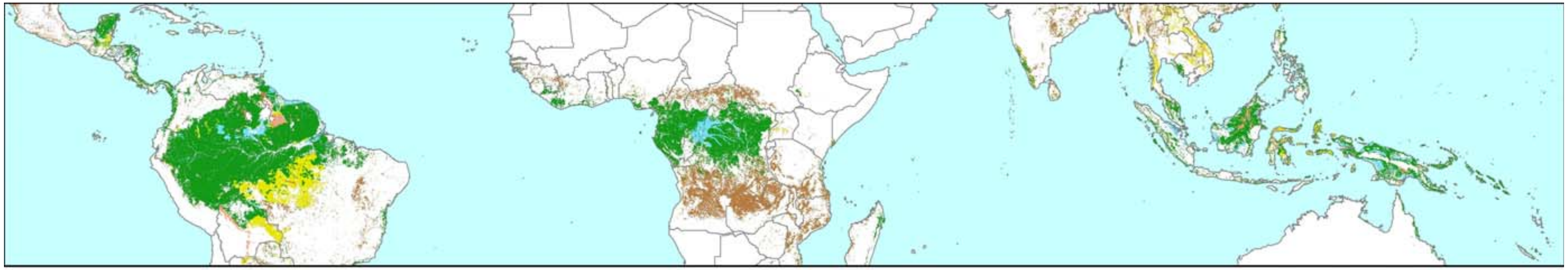
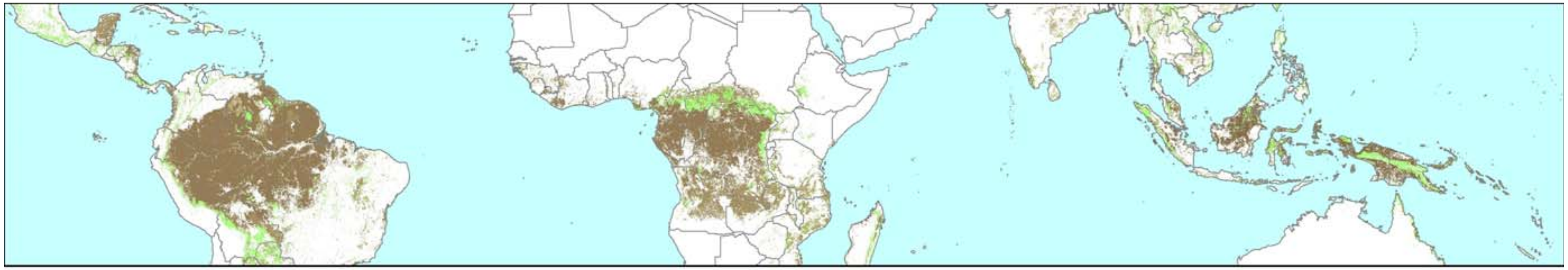


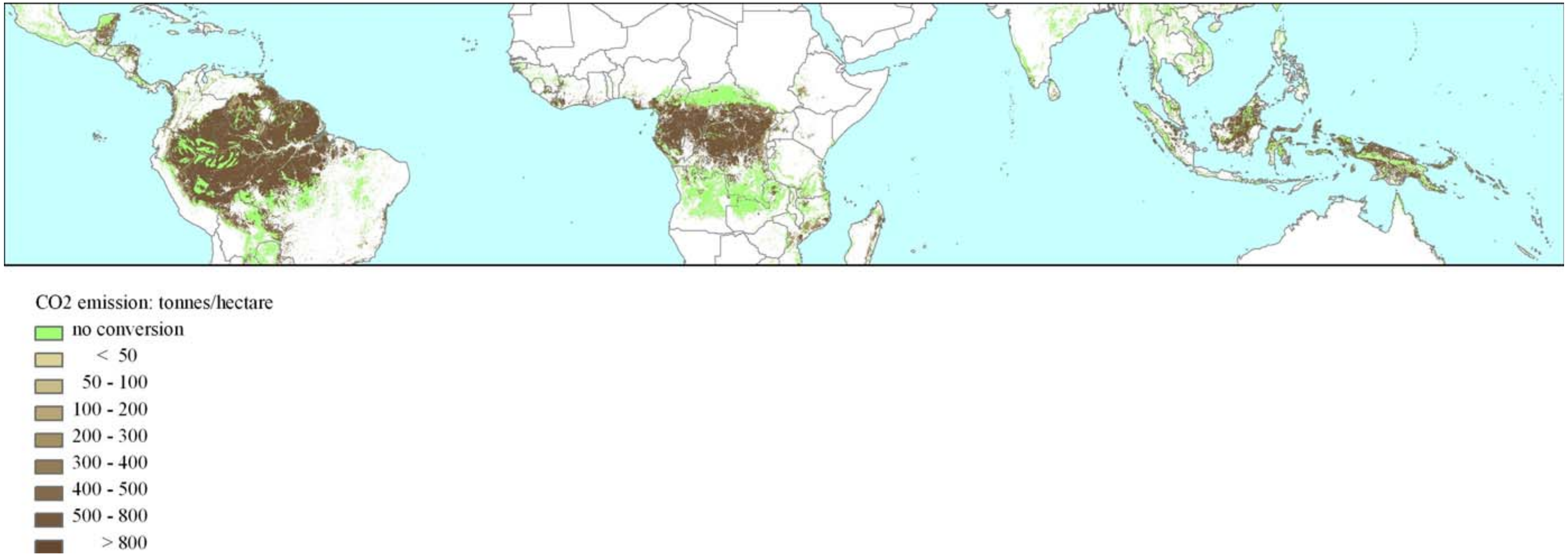
Figure 10: Potential CO_2 emissions (Gt) from conversion of vulnerable tropical forests to the most valuable land use at each location



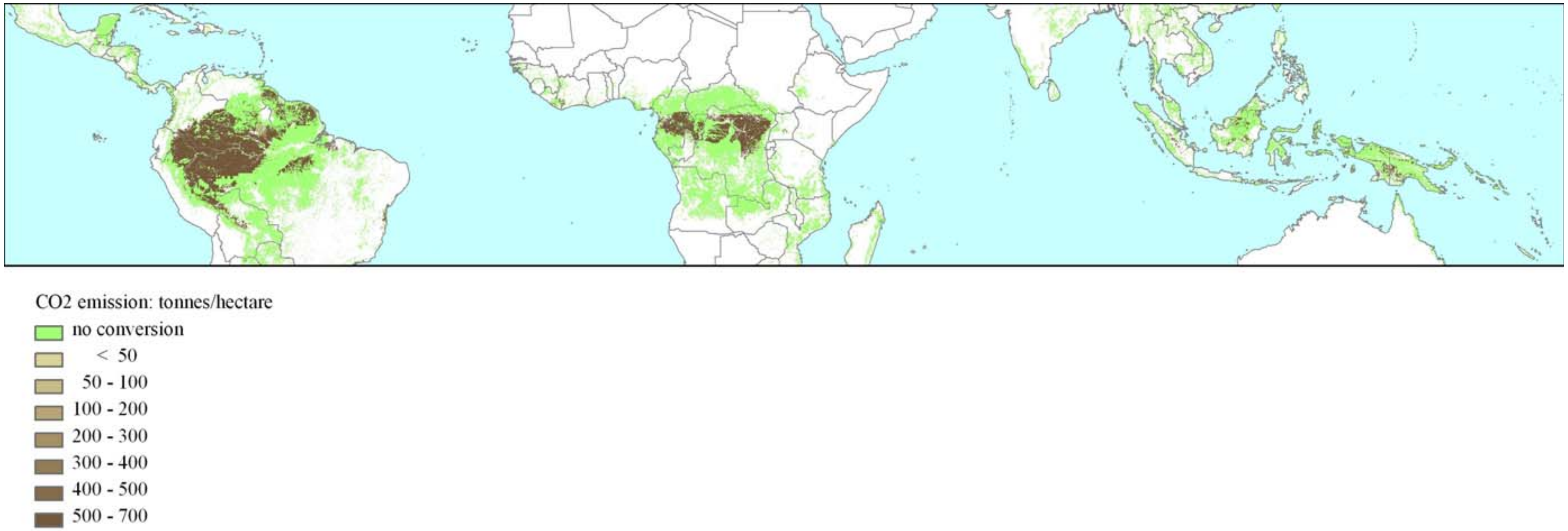
Map 3: Tropical forest estimated to be vulnerable to logging (based on type and slope)



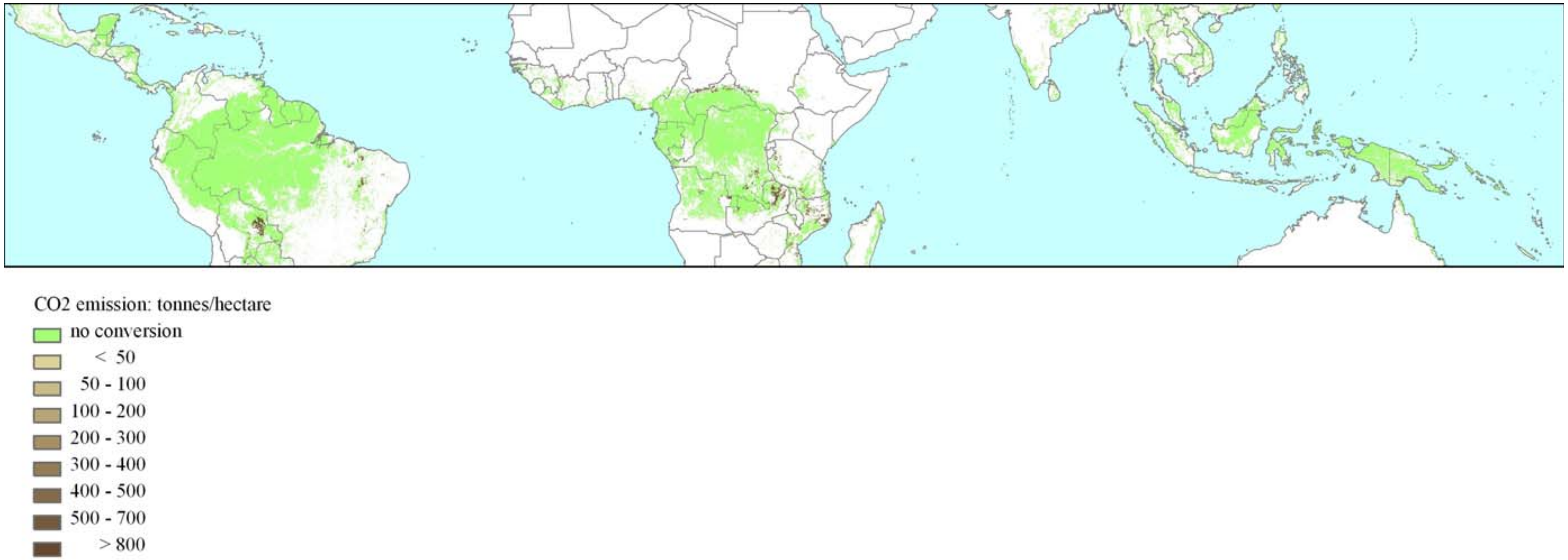
Map 4: Potential CO_2 emissions from logging of all vulnerable tropical forest



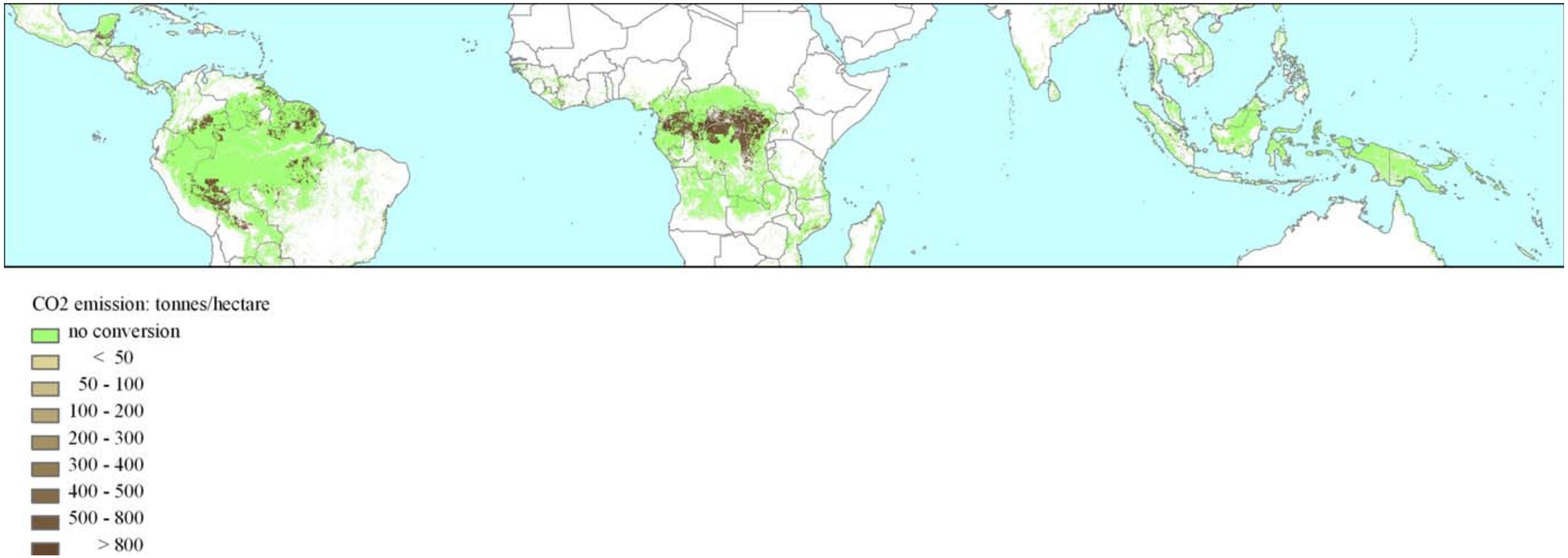
Map 5: Potential CO_2 emissions from conversion of all vulnerable tropical forest to pasture



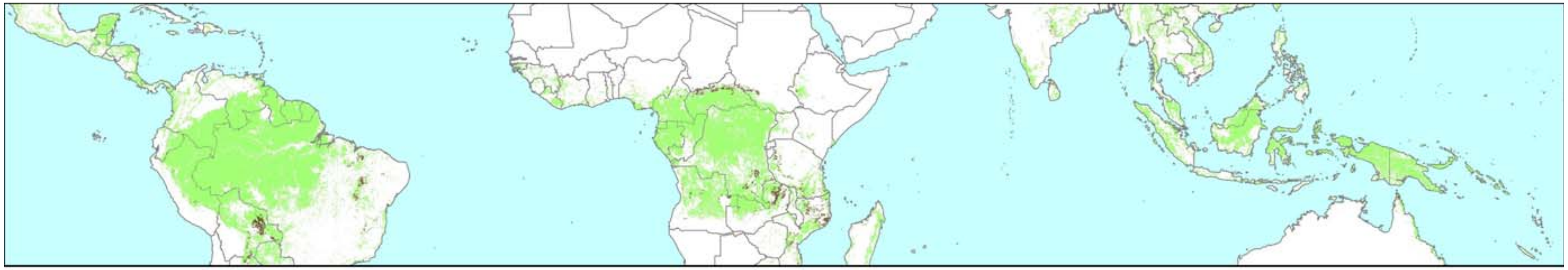
Map 6: Potential CO_2 emissions from conversion of all vulnerable tropical forest to rainfed oil palm plantation



Map 7: Potential CO_2 emissions from conversion of all vulnerable tropical forest to rainfed soybean



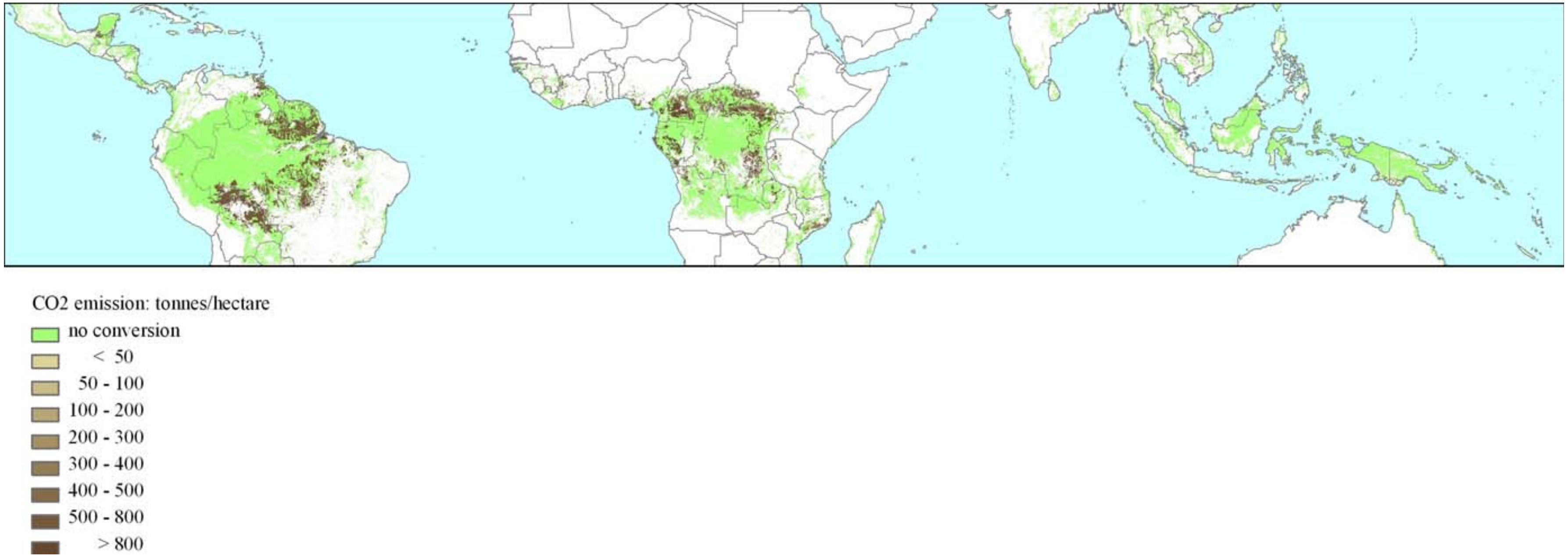
Map 8: Potential CO_2 emissions from conversion of all vulnerable tropical forest to rainfed sugar cane



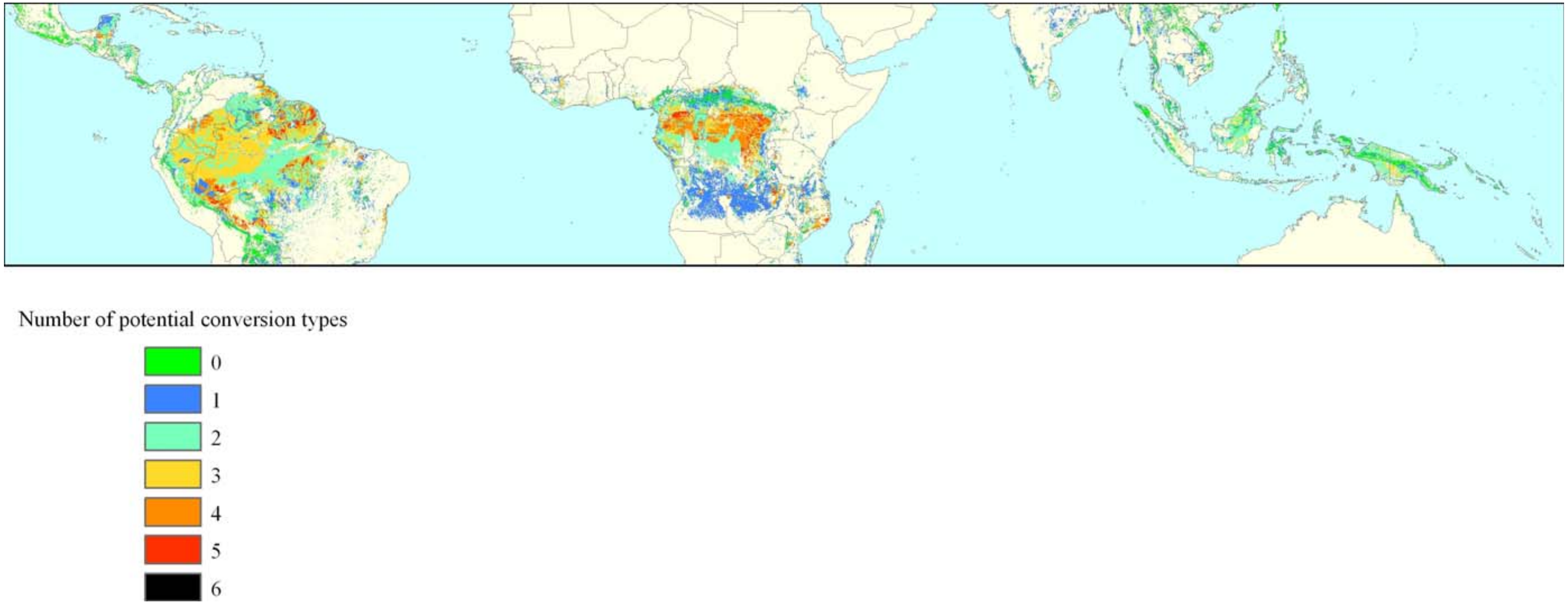
CO2 emission: tonnes/hectare

- no conversion
- < 50
- 50 - 100
- 100 - 200
- 200 - 300
- 300 - 400
- 400 - 500
- 500 - 800
- > 800

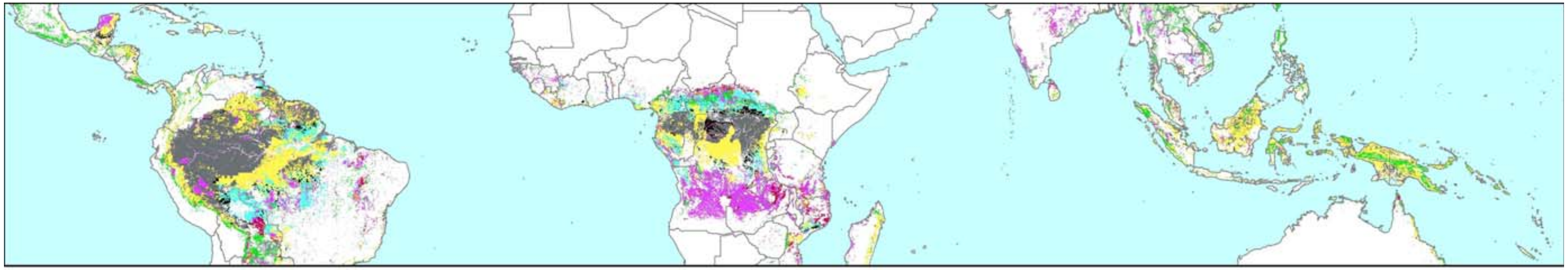
Map 9: Potential CO_2 emissions from conversion of all vulnerable tropical forest to rainfed maize



Map 10: Potential CO_2 emissions from conversion of all vulnerable tropical forest to rainfed rice

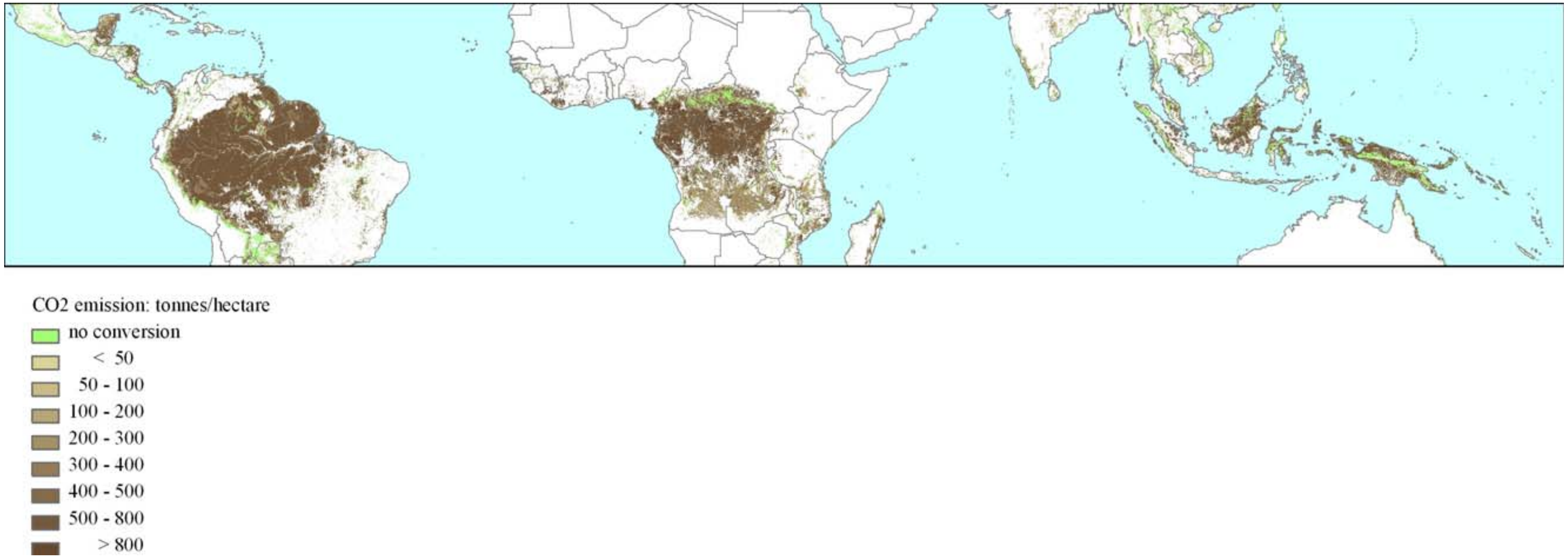


Map 11: Tropical forest area vulnerable to conversion to multiple land uses



Conversion type:
1. Oil palm
2. Soybean
3. Sugarcane
4. Maize
5. Rice
6. Pasture
7. Logging
8. None

Map 12: Most valuable suitable land use for tropical forest area



Map 13: CO_2 emissions resulting from conversion of vulnerable tropical forest to most valuable land use

Africa

Table 9: Area of forest of each type vulnerable to conversion each land use in tropical Africa (km^2)

Forest type	Total forest area	Soybean	Oil palm	Sugarcane	Maize	Rice	Pasture	Logging
1. Tropical lowland evergreen broadleaf rain forest	1,906,471	2,881	703,770	693,229	5,148	443,956	1,717,022	1,889,793
2. Tropical lower montane forest	41,765	409	500	1,484	381	5,171	18,149	37,844
3. Tropical upper montane forest	99,978	89	6,286	4,372	915	3,814	84,673	0
4. Tropical freshwater swamp forest	187,322	30	71,452	115,084	31	9,938	175,491	187,316
5. Tropical semi-evergreen moist broadleaf forest	10,892	103	1,621	1,611	103	996	9,011	10,389
8. Tropical deciduous/semi-deciduous broadleaf forest	1,919,498	209,590	2,351	37,721	230,460	370,538	353,870	1,858,093
10. Tropical thorn forest	731	0	0	0	0	0	0	0
11. Mosaic forest / other natural cover	361,186	2,050	6,298	41,309	5,546	176,095	175,968	0
12. Tropical sparse trees/parkland	176,083	30,640	803	4,243	32,613	39,997	63,562	0
13. Tropical mangrove	23,728	553	91	73	563	2,931	13,727	0
14. Unclassified tropical forest	93	1	3	1	1	4	33	0
Total forest	**4,727,747**	**246,346**	**793,175**	**899,127**	**275,761**	**1,053,440**	**2,611,506**	**3,983,435**

Table 10: Potential CO_2 emissions in tropical Africa from conversion of all vulnerable forest to each land use (Gt)

Forest type	Soybean	Oil palm	Sugarcane	Maize	Rice	Pasture	Logging
1. Tropical lowland evergreen broadleaf rain forest	0.2	37.6	54.1	0.3	34.6	117.3	66.3
2. Tropical lower montane forest	0.0	0.0	0.1	0.0	0.4	0.7	1.0
3. Tropical upper montane forest	0.0	0.2	0.2	0.0	0.2	2.2	0.0
4. Tropical freshwater swamp forest	0.0	4.1	10.2	0.0	0.9	12.3	6.8
5. Tropical semi-evergreen moist broadleaf forest	0.0	0.1	0.1	0.0	0.1	0.4	0.2
8. Tropical deciduous/semi-deciduous broadleaf forest	11.5	0.1	2.3	12.7	22.9	17.3	48.6
10. Tropical thorn forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11. Mosaic forest / other natural cover	0.1	0.1	1.8	0.2	7.6	5.8	0.0
12. Tropical sparse trees/parkland	1.6	0.0	0.2	1.7	2.0	2.5	0.0
13. Tropical mangrove	0.0	0.0	0.0	0.0	0.2	0.9	0.0
14. Unclassified tropical forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total for all forest	**13.4**	**42.3**	**69.1**	**14.9**	**68.8**	**159.3**	**122.9**

Table 11: Potential CO_2 emissions in tropical Africa from conversion of all vulnerable forest, excluding protected areas [categories I to IV for logging, and all categories for agriculture], to each land use (Gt)

Forest type	Soybean	Oil palm	Sugarcane	Maize	Rice	Pasture	Logging
1. Tropical lowland evergreen broadleaf rain forest	0.1	31.8	45.2	0.2	27.6	96.4	61.5
2. Tropical lower montane forest	0.0	0.0	0.1	0.0	0.4	0.6	1.0
3. Tropical upper montane forest	0.0	0.2	0.2	0.0	0.1	1.7	0.0
4. Tropical freshwater swamp forest	0.0	3.8	9.7	0.0	0.9	11.4	6.6
5. Tropical semi-evergreen moist broadleaf forest	0.0	0.1	0.1	0.0	0.0	0.3	0.2
8. Tropical deciduous/semi-deciduous broadleaf forest	8.9	0.1	2.2	9.8	20.0	15.1	46.5
10. Tropical thorn forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11. Mosaic forest / other natural cover	0.1	0.1	1.5	0.2	6.1	4.6	0.0
12. Tropical sparse trees/parkland	1.2	0.0	0.2	1.3	1.7	2.2	0.0
13. Tropical mangrove	0.0	0.0	0.0	0.0	0.2	0.8	0.0
14. Unclassified tropical forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total for all forest	**10.4**	**36.1**	**59.0**	**11.5**	**57.0**	**133.1**	**115.7**

Americas

Table 12: Area of forest of each type vulnerable to conversion to each land use in tropical Latin America (km^2)

Forest type	Total forest area	Soybean	Oil palm	Sugarcane	Maize	Rice	Pasture	Logging
1. Tropical lowland evergreen broadleaf rain forest	4,756,820	13,058	2,141,217	512,675	20,795	804,129	3,993,671	4,662,054
2. Tropical lower montane forest	250,256	3,890	24,688	19,233	4,083	30,685	118,786	144,377
3. Tropical upper montane forest	250,750	1,266	9,684	7,385	3,286	6,815	87,382	0
4. Tropical freshwater swamp forest	264,876	116	139,246	28,392	297	45,421	227,474	263,982
5. Tropical semi-evergreen moist broadleaf forest	888,212	30,114	96,873	89,629	34,517	355,929	619,157	882,965
6. Tropical mixed needleleaf/broadleaf forest	19,594	242	117	183	402	556	6,180	8,301
7. Tropical needleleaf forest	40,607	424	2,011	4,217	664	4,453	20,496	26,316
8. Tropical deciduous/semi-deciduous broadleaf forest	362,956	16,924	11,454	10,962	27,804	68,523	109,578	335,906
9. Tropical sclerophyllous dry forest	163,039	20,707	6,574	1,944	26,404	7,857	34,725	0
10. Tropical thorn forest	1,539	36	0	27	97	11	545	0
12. Tropical sparse trees/parkland	235,535	6,344	3,605	5,201	9,288	46,950	66,466	0
13. Tropical mangrove	24,277	591	1,476	1,735	970	3,217	9,209	0
14. Unclassified tropical forest	371	0	9	1	13	20	72	0
Total for all forest	**7,258,832**	**93,712**	**2,436,954**	**681,584**	**128,620**	**1,374,566**	**5,293,741**	**6,323,901**

Table 13: Potential CO_2 emissions in tropical Latin America from conversion of all vulnerable forest to each land use (Gt)

Forest type	Soybean	Oil palm	Sugarcane	Maize	Rice	Pasture	Logging
1. Tropical lowland evergreen broadleaf rain forest	0.7	108.6	37.0	1.1	58.7	256.6	154.8
2. Tropical lower montane forest	0.2	1.1	1.3	0.2	2.2	6.2	3.9
3. Tropical upper montane forest	0.1	0.3	0.4	0.1	0.3	3.4	0.0
4. Tropical freshwater swamp forest	0.0	6.4	1.8	0.0	3.0	13.4	8.1
5. Tropical semi-evergreen moist broadleaf forest	1.6	4.8	6.3	1.8	25.0	38.9	28.5
6. Tropical mixed needleleaf/broadleaf forest	0.0	0.0	0.0	0.0	0.0	0.3	0.2
7. Tropical needleleaf forest	0.0	0.1	0.2	0.0	0.2	0.9	0.6
8. Tropical deciduous/semi-deciduous broadleaf forest	0.8	0.4	0.6	1.3	3.7	4.9	7.5
9. Tropical sclerophyllous dry forest	1.1	0.3	0.1	1.4	0.4	1.8	0.0
10. Tropical thorn forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12. Tropical sparse trees/parkland	0.3	0.2	0.3	0.4	2.5	3.0	0.0
13. Tropical mangrove	0.0	0.0	0.1	0.1	0.2	0.4	0.0
14. Unclassified tropical forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total for all forest	**4.7**	**122.2**	**48.1**	**6.5**	**96.4**	**329.8**	**203.5**

Table 14: Potential CO_2 emissions in tropical Latin America from conversion of all vulnerable forest, excluding protected areas [categories I to IV for logging, and all categories for agriculture], to each land use (Gt)

Forest type	Soybean	Oil palm	Sugarcane	Maize	Rice	Pasture	Logging
1. Tropical lowland evergreen broadleaf rain forest	0.5	67.4	21.1	0.9	29.0	147.5	138.4
2. Tropical lower montane forest	0.1	0.8	0.9	0.1	2.2	4.9	3.3
3. Tropical upper montane forest	0.0	0.0	0.1	0.1	0.1	1.3	0.0
4. Tropical freshwater swamp forest	0.0	4.1	1.1	0.0	2.0	9.1	7.5
5. Tropical semi-evergreen moist broadleaf forest	1.5	1.3	2.5	1.7	12.7	16.8	24.2
6. Tropical mixed needleleaf/broadleaf forest	0.0	0.0	0.0	0.0	0.0	0.2	0.2
7. Tropical needleleaf forest	0.0	0.1	0.2	0.0	0.2	0.8	0.6
8. Tropical deciduous/semi-deciduous broadleaf forest	0.6	0.1	0.3	1.1	2.9	3.0	7.0
9. Tropical sclerophyllous dry forest	0.9	0.3	0.1	1.2	0.4	1.6	0.0
10. Tropical thorn forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12. Tropical sparse trees/parkland	0.2	0.1	0.2	0.4	1.5	2.2	0.0
13. Tropical mangrove	0.0	0.0	0.1	0.0	0.1	0.2	0.0
14. Unclassified tropical forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total for all forest	**4.1**	**74.2**	**26.7**	**5.7**	**51.1**	**187.7**	**181.0**

Asia

Table 15: Area of forest of each type vulnerable to conversion to each land use in tropical Asia (km^2)

Forest type	Total forest area	Soybean	Oil palm	Sugarcane	Maize	Rice	Pasture	Logging
1. Tropical lowland evergreen broadleaf rain forest	1,142,293	783	153,547	17,363	993	13,324	790,911	953,846
2. Tropical lower montane forest	192,758	0	3,352	58	0	86	63,705	90,146
3. Tropical upper montane forest	173,041	0	364	0	0	51	47,987	0
4. Tropical freshwater swamp forest	178,240	0	21,124	4,018	0	1,436	167,846	177,265
5. Tropical semi-evergreen moist broadleaf forest	284,736	269	2,906	600	372	6,038	75,098	157,080
7. Tropical needleleaf forest	5,818	0	0	0	0	21	721	1,812
8. Tropical deciduous/semi-deciduous broadleaf forest	339,429	11,458	288	904	17,625	17,445	51,383	251,160
9. Tropical sclerophyllous dry forest	387	13	0	0	19	0	0	0
10. Tropical thorn forest	1,535	68	0	0	89	0	0	0
12. Tropical sparse trees/parkland	8,589	339	269	11	370	2,835	5,198	0
13. Tropical mangrove	39,737	73	1,318	1,523	88	582	23,921	0
14. Unclassified tropical forest	2,572	0	45	12	0	7	683	0
Total for all forest	2,369,135	13,003	183,213	24,489	19,556	41,825	1,227,453	1,631,309

Table 16: Potential CO_2 emissions in tropical Asia from conversion of all vulnerable forest to each land use (Gt)

Forest type	Soybean	Oil palm	Sugarcane	Maize	Rice	Pasture	Logging
1. Tropical lowland evergreen broadleaf rain forest	0.0	8.7	1.3	0.0	0.9	55.5	34.1
2. Tropical lower montane forest	0.0	0.2	0.0	0.0	0.0	4.0	2.8
3. Tropical upper montane forest	0.0	0.0	0.0	0.0	0.0	2.5	0.0
4. Tropical freshwater swamp forest	0.0	1.3	0.4	0.0	0.0	12.5	6.8
5. Tropical semi-evergreen moist broadleaf forest	0.0	0.1	0.0	0.0	0.2	4.4	4.0
7. Tropical needleleaf forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8. Tropical deciduous/semi-deciduous broadleaf forest	0.4	0.0	0.0	0.6	0.8	2.0	4.3
9. Tropical sclerophyllous dry forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10. Tropical thorn forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12. Tropical sparse trees/parkland	0.0	0.0	0.0	0.0	0.2	0.3	0.0
13. Tropical mangrove	0.0	0.1	0.1	0.0	0.0	1.5	0.0
14. Unclassified tropical forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total for all forest	**0.5**	**10.4**	**1.9**	**0.7**	**2.2**	**82.7**	**52.0**

Table 17: Potential CO_2 emissions in tropical Asia from conversion of all vulnerable forest, excluding protected areas [categories I to IV for logging, and all categories for agriculture], to each land use (Gt)

Forest type	Soybean	Oil palm	Sugarcane	Maize	Rice	Pasture	Logging
1. Tropical lowland evergreen broadleaf rain forest	0.0	7.8	1.2	0.0	0.8	47.9	31.7
2. Tropical lower montane forest	0.0	0.2	0.0	0.0	0.0	3.1	2.6
3. Tropical upper montane forest	0.0	0.0	0.0	0.0	0.0	1.9	0.0
4. Tropical freshwater swamp forest	0.0	1.1	0.4	0.0	0.0	10.4	6.2
5. Tropical semi-evergreen moist broadleaf forest	0.0	0.1	0.0	0.0	0.2	3.6	3.4
7. Tropical needleleaf forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8. Tropical deciduous/semi-deciduous broadleaf forest	0.3	0.0	0.0	0.5	0.6	1.7	3.7
9. Tropical sclerophyllous dry forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10. Tropical thorn forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12. Tropical sparse trees/parkland	0.0	0.0	0.0	0.0	0.1	0.2	0.0
13. Tropical mangrove	0.0	0.1	0.1	0.0	0.0	1.2	0.0
14. Unclassified tropical forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total for all forest	**0.4**	**9.3**	**1.7**	**0.6**	**1.8**	**70.1**	**47.6**

Australia, Oceania and Hawaii

Table 18: Area of forest of each type vulnerable to conversion each land use in tropical Australia, Oceania and Hawaii (km^2)

Forest type	Total forest area	Soybean	Oil palm	Sugarcane	Maize	Rice	Pasture	Logging
1. Tropical lowland evergreen broadleaf rain forest	24,524	2,389	0	60	2,861	317	16,751	23,217
2. Tropical lower montane forest	252	0	0	0	0	0	105	104
3. Tropical upper montane forest	960	5	0	0	20	22	777	0
4. Tropical freshwater swamp forest	4	0	0	0	0	0	4	4
8. Tropical deciduous/semi-deciduous broadleaf forest	407	164	0	0	166	57	106	407
9. Tropical sclerophyllous dry forest	27,547	6,931	0	2	7,289	899	7,281	0
12. Tropical sparse trees/parkland	12,372	1,504	15	1	1,713	135	5,014	0
13. Tropical mangrove	5,618	1,071	0	57	1,341	259	1,313	0
14. Unclassified tropical forest	36	2	0	1	2	1	4	0
Total for all forest	71,720	12,066	15	121	13,392	1,690	31,355	23,732

Table 19: Potential CO_2 emissions in tropical Australia, Oceania and Hawaii from conversion of all vulnerable forest to each land use (Gt)

Forest type	Soybean	Oil palm	Sugarcane	Maize	Rice	Pasture	Logging
1. Tropical lowland evergreen broadleaf rain forest	0.1	0.0	0.0	0.2	0.0	1.2	0.8
2. Tropical lower montane forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3. Tropical upper montane forest	0.0	0.0	0.0	0.0	0.0	0.1	0.0
4. Tropical freshwater swamp forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8. Tropical deciduous/semi-deciduous broadleaf forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9. Tropical sclerophyllous dry forest	0.3	0.0	0.0	0.3	0.0	0.4	0.0
12. Tropical sparse trees/parkland	0.1	0.0	0.0	0.1	0.0	0.2	0.0
13. Tropical mangrove	0.0	0.0	0.0	0.1	0.0	0.1	0.0
14. Unclassified tropical forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total for all forest	**0.6**	**0.0**	**0.0**	**0.6**	**0.1**	**1.9**	**0.8**

Table 20: Potential CO_2 emissions in tropical Australia, Oceania and Hawaii from conversion of all vulnerable forest, excluding protected areas [categories I to IV for logging, and all categories for agriculture], to each land use (Gt)

Forest type	Soybean	Oil palm	Sugarcane	Maize	Rice	Pasture	Logging
1. Tropical lowland evergreen broadleaf rain forest	0.1	0.0	0.0	0.1	0.0	0.9	0.6
2. Tropical lower montane forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3. Tropical upper montane forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4. Tropical freshwater swamp forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8. Tropical deciduous/semi-deciduous broadleaf forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9. Tropical sclerophyllous dry forest	0.2	0.0	0.0	0.2	0.0	0.3	0.0
12. Tropical sparse trees/parkland	0.1	0.0	0.0	0.1	0.0	0.2	0.0
13. Tropical mangrove	0.0	0.0	0.0	0.0	0.0	0.1	0.0
14. Unclassified tropical forest	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total for all forest	**0.4**	**0.0**	**0.0**	**0.5**	**0.1**	**1.6**	**0.6**

Caveats

The following considerations are important in interpreting and using the maps and statistics contained in this report.

- Nationally available data will frequently be more accurate than the national subsets from standardised global datasets. Therefore, the results from this analysis are most appropriate for drawing regional rather than national scale conclusions.
- Full conversion or logging of all available land is unlikely in most countries within the next few decades, partly because environmental indicators tend to improve as national wealth increases (Stern 2004, Rudel 2005). The only factor that is taken into account here in assessing vulnerability is the suitability of land for conversion – there is no measurement of supply and demand, or the relative costs of conversion at different locations. The rate at which forests were converted would have a strong impact on the emissions curve.
- Further, sequential land uses have not been addressed – e.g. logging is frequently a precursor to conversion; pasture is sometimes a precursor to other agricultural uses.
- The forest map addresses closed forest only, so will indicate a smaller global area than FAO statistics, which use a 10% canopy cover definition. A 30% threshold was favoured because more uncertainty is attached to mapping lower cover classes and the carbon content of greatest concern is for closed forests. Resolution-related differences between the maps used have resulted in the loss of some small areas of forest land from the analysis, largely along coastlines.
- The forest classes in the revised map are those employed in the original Global Forest Map (UNEP-WCMC 2000), with the addition of 'mosaic of tree cover and other natural vegetation' and 'unclassified tropical forest'. These reflect areas of forest not represented in the original map, which require further investigation to resolve their status and classification. All forest represented in the map has >=30% canopy cover according to MODIS remote sensing data.
- The agricultural suitability maps are based on a half-degree latitude/longitude world climate data set, 5' soils data derived from the digital version of the FAO Soil Map of the World, the 30" Global Land Cover Characteristics Database, and a 30" digital elevation data set. The quality and reliability of these data sets, in particular the world soil map, are uneven across regions (van Velthuizen et al. 2007).
- In addition, the suitability maps do not take into account the potential development of new cultivars. This effect is already visible in the map of soybean suitability, which excludes areas of the Amazon in which it is now feasible to grow recently developed varieties of soybean (Cerri *et al*. 2007).
- The actual distribution of agriculture and logging differs from the theoretical suitability maps, because in reality land use is based on local needs and customs as well as suitability. Analyses using the GAEZ indicate that large populations are making use of land for agriculture in areas where suitability is low (van Velthuizen et al. 2007). The present analysis therefore underestimates the potential for conversion of forest to subsistence agriculture. Similar considerations apply for timber extraction. The opportunity costs of avoiding land use change in these marginal areas ought to be smaller than those in areas suitable for commercial enterprise. However, considerations of equity and land rights should play a major role in developing mechanisms for REDD implementation.
- The global nature of the suitability maps can also be also a cause of error, meaning that on-the-ground suitability will differ from the global overview. For example, commercially valuable timber is extracted from some upper montane forests.
- The carbon estimates take little account of any forest reversion/regeneration, which is particularly likely on abandoned pasture and in regions with dynamic land use.
- Disturbed forest in Asia is likely to retain less carbon than that in Africa or Latin America, as it is clear that logging intensities are much greater in this region (Pinard &

Putz 1996, Curran *et al.* 2004, Bertault & Sist 1997). This distinction has not been made in the current analysis.

- Clearing for pulpwood or timber plantations have not been directly addressed in this analysis. This is a locally important pressure in southeast Asia, but relatively minor on a global scale.
- Average carbon stock values have been used to estimate emissions. Consequently, forest carbon stocks and conversion emissions for a particular area may be overestimated or underestimated if the forests in question differ from the average forest strata values (Houghton 2005).
- Soil carbon losses from logging and pasture have not been accounted for, due to a lack of adequate global statistics and to the strong influence of management practices. The impacts of post-conversion management in Amazonia were discussed by Fearnside & Barbosa (1998), who reported an 8-49% loss in soil carbon through conversion of forest to pasture with typical management, but a 3-58% gain in areas with ideal management practices. Indeed, it has been suggested that in the long term, pastureland has the same potential to store soil organic carbon as forest (Guo & Gifford 2002). Wetland and other peat soils are a special case with potentially large emissions following conversion that are difficult to prevent without restoration.
- Emissions of greenhouse gases other than carbon dioxide have not been estimated in this analysis. Methane and nitrous oxide emissions from livestock keeping on pasture, for example, would make a substantial additional contribution to global warming if all this conversion were to take place.

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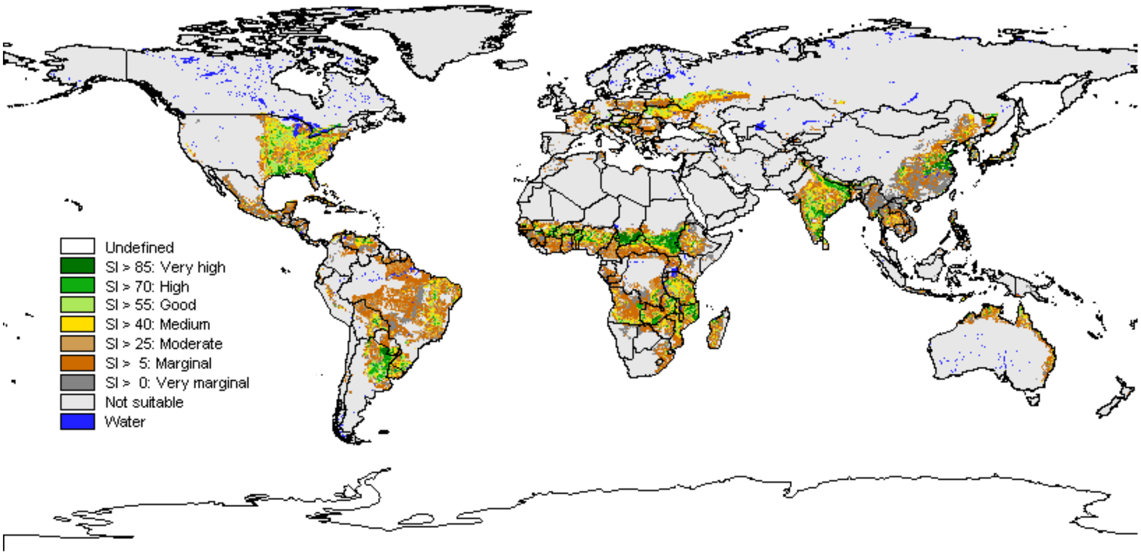
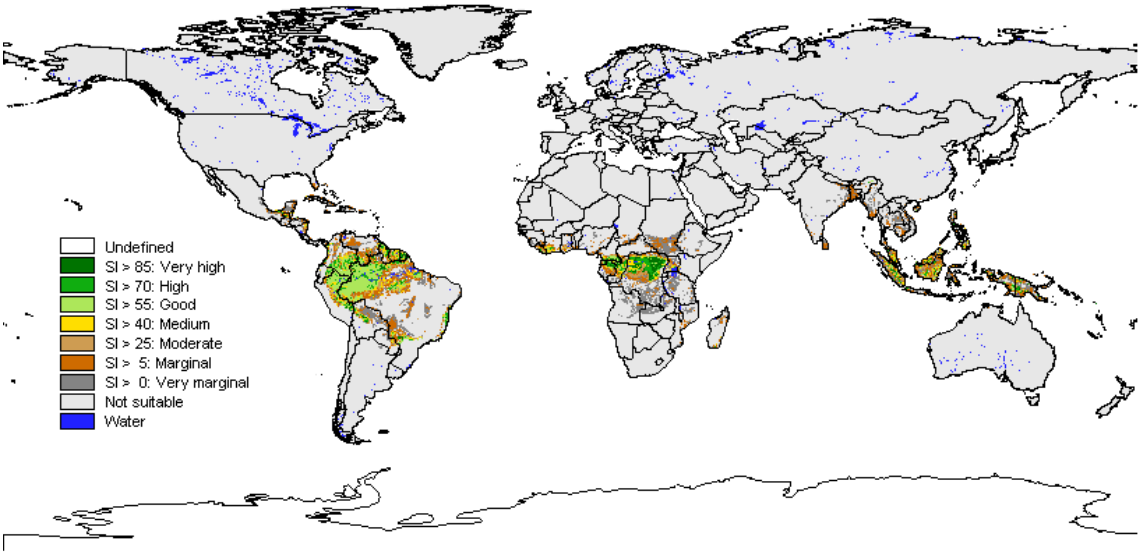
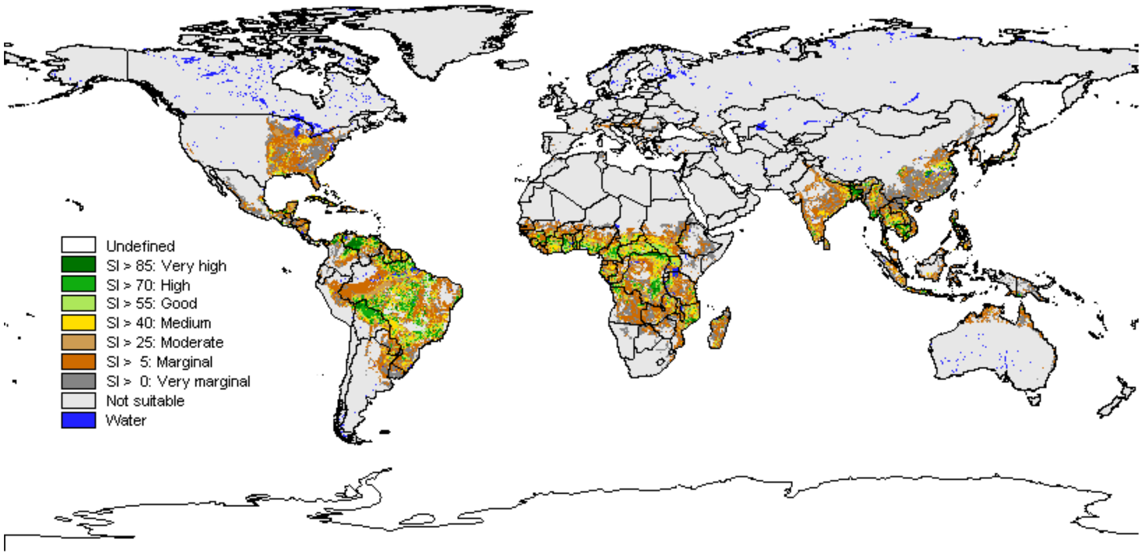
Annex: input maps



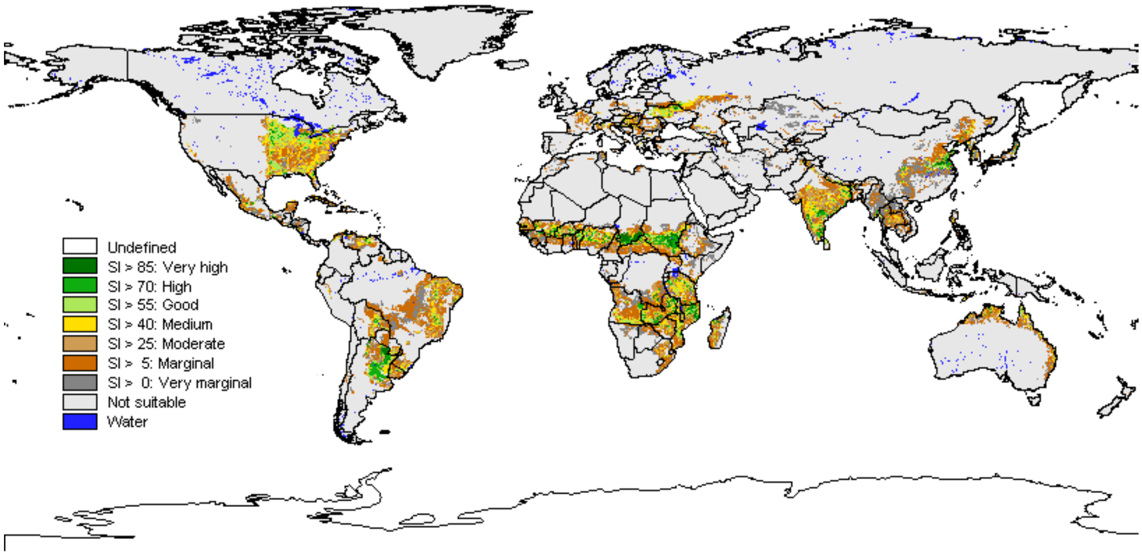
Map A1: Suitability index for rainfed grain maize (maximising technology mix) (FAO/IIASA)



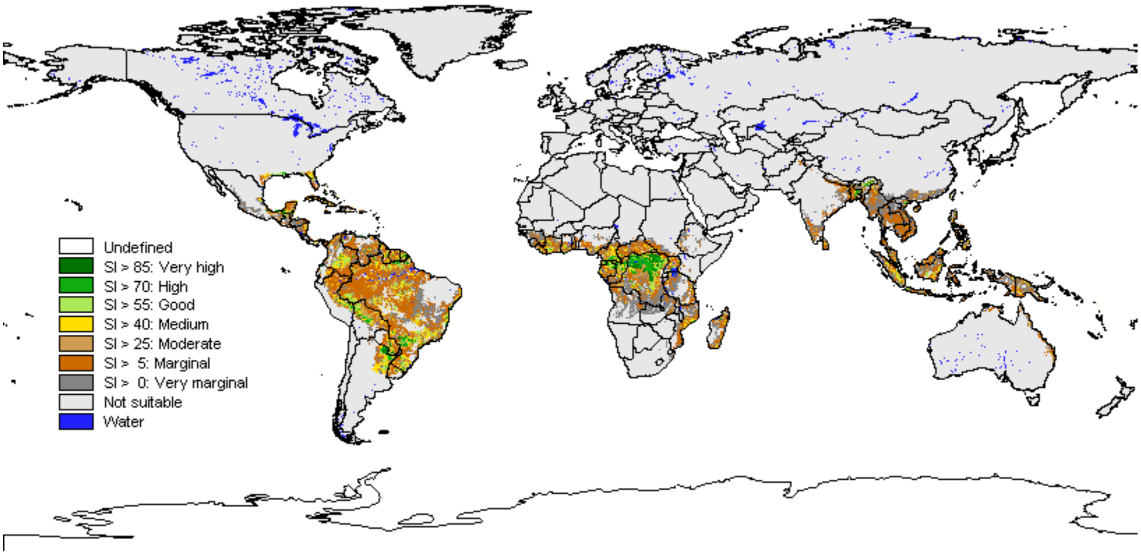
Map A2: Suitability index for rainfed oil palm (maximising technology mix) (FAO/IIASA)



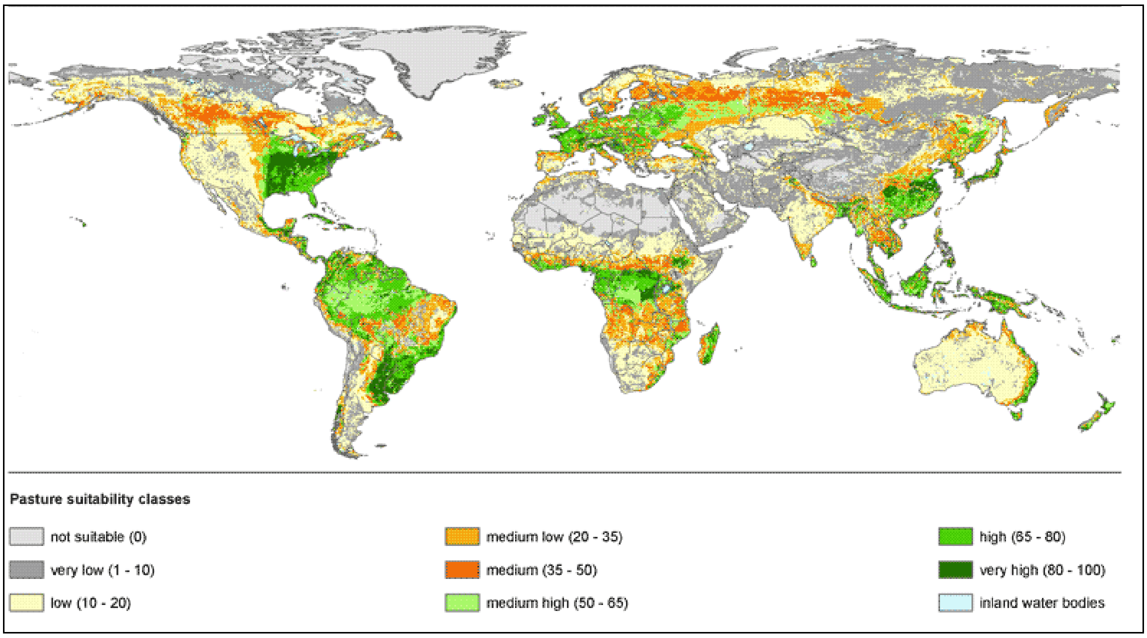
Map A3: Suitability index for rainfed rice (maximising technology mix) (FAO/IIASA)



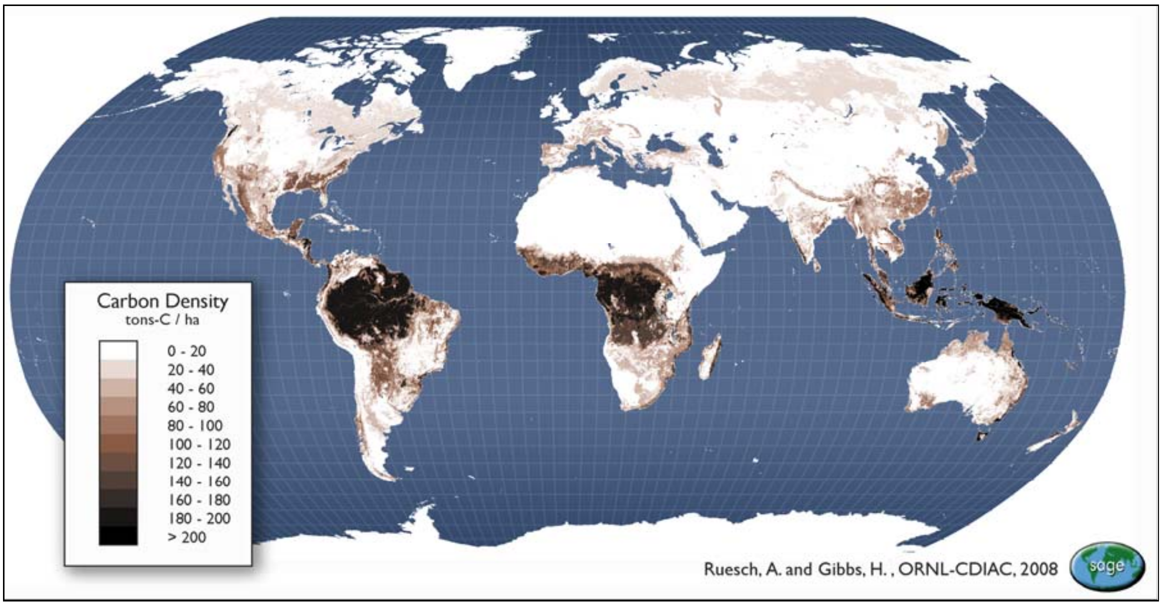
Map A4: Suitability index for rainfed soybean (maximising technology mix) (FAO/IIASA)



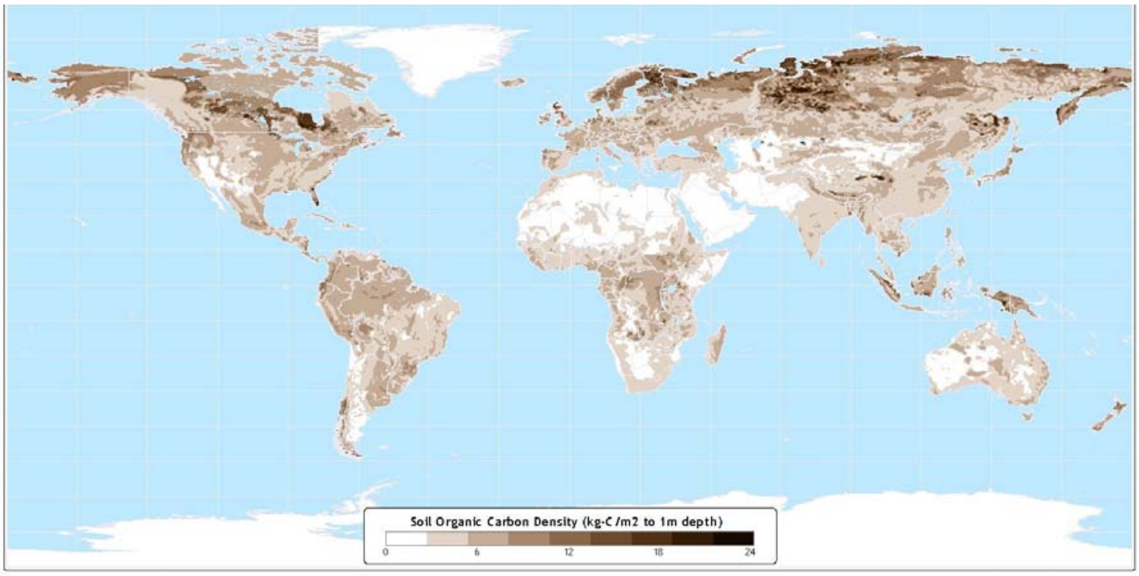
Map A5: Suitability index for rainfed sugar cane (maximising technology mix) (FAO/IIASA)



Map A6: Suitability index for pasture (FAO/IIASA)



Map A7: Above and below-ground living biomass carbon stocks, 2000



Map A8: Organic soil carbon density (IGBP)