Asia-Pacific
Economic Cooperation

Assessment of Biomass Resources from Marginal Lands in APEC Economies

Energy Working Group

August 2009

This report was prepared for the APEC Energy Working Group under EWG 11/2008A by:

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APEC#209-RE-01.4

Acknowledgments

The authors would like to acknowledge and thank the project overseer, Mr. Jeffrey Skeer (Department of Energy, USA and chair of the APEC Biofuels Task Force), for his support, review, and guidance throughout this project. We also thank Mr. Mark Stumborg from Agriculture and Agri-Food Canada for his review and recommendations.

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Abbreviations and Acronyms

APEC - Asia-Pacific Economic Cooperation

CO_2 – Carbon Dioxide

ENSO - El Nino Southern Oscillation

FAO - Food and Agriculture Organization

GAEZ – Global Agro-Ecological Zones

GHG – Greenhouse gases

GIS – geographic information system

IIASA - International Institute for Applied Systems Analysis

NPP – Net Primary Productivity

NREL - National Renewable Energy Laboratory (of the U.S. Department of Energy)

PNG - Papua New Guinea

RS – remote sensing

UNEP – United Nations Environmental Programme

USDA – United States Department of Agriculture

Units of Measure

g – gram

Gt – Gigatonne (10^9 tonne)

ha – hectare

hm^3 – cubic hectometer or 1,000,000 m^3 or 10^9 L, described in some sources as a GL (Gigaliter)

m^2 – square meter

m^3 – cubic meter

MJ – Megajoule (10^6 joule)

Mt – Megatonne (10^6 tonne)

km^2 – square kilometer

Tonne (t) - metric ton

Executive Summary

Marginal lands have received an increased attention by the bioenergy industry as an alternative to cropland for feedstock supply that could help to address the food vs. fuel debate challenging the industry's further development. Literature suggests that Asia-Pacific Economic Cooperation (APEC) economies have vast marginal lands available, which may hold potential for the production of biofuels feedstock. However, the term "marginal land" has been used quite loosely without a concrete definition. Moreover, in many economies, the extent and characteristics of these lands have not been systematically assessed, nor has their suitability for biofuels crop production been evaluated.

The goal of this study is to examine the marginal lands in APEC economies and evaluate their biomass productivity potential. Twelve categories of marginal lands are identified using the Global Agro-Ecological Zones system of the United Nations Food and Agriculture Organization. Numerous exclusions are applied using state-of-the-art geographic information systems (GIS) to estimate the *available* marginal lands in APEC economies. The analysis estimates that about 4 million km^2 (400 million ha) of marginal lands are available in the APEC region, representing 6.5% of the total land area. Economies with the largest marginal lands include Australia (13.5% of total land area); Canada (4%); China (5%); Russia (2%); and the United States (13%).

The study's biomass production assessment methodology takes into account a combination of the current vegetation cover and a calculation of the net primary productivity (NPP). The NPP incorporates a fixed middle range of radiation use efficiency and adjusts for air temperature. It is derived from extensive data sets and translated into the annual yield of a lignocellulosic biomass, typical of grasses such as switchgrass and other thin-stemmed perennials or thick-stemmed grasses in tropical areas. Other lignocellulosics that would be similar are short-rotation tree species with willow and poplar as examples in temperate regions and eucalyptus in more tropical environments. These crop types meet the criteria of non-edible crops and will give the highest biomass potential.

This study estimates the total annual biomass resource potential on marginal lands in APEC economies to be about 1.3 Gt, which converts roughly into 540 hm^3 of ethanol fuel or 260 Mt of gasoline equivalent. By comparison, APEC uses about 621 Mt of gasoline and crude oil import

is about 1.3 Gt annually (IEA 2006). So the ethanol potential from marginal lands could displace two-fifths of the region's gasoline consumption and one-fifth of its crude oil imports.

Many economies could substitute a substantial volume of their current gasoline consumption and crude oil imports with ethanol from marginal lands, as illustrated in the Appendix. These include Australia; Chile; New Zealand; Peru; and Viet Nam. But there could be technical or economic restrictions on the use of these lands, which suggests that only a portion of this potential can be realized. This portion would be different in each economy and could be determined by a detailed techno-economic feasibility assessment, which is beyond the scope of this study.

Previous work by the authors (Milbrandt, A., Overend, R. 2008) evaluated the ethanol potential from existing lignocellulosic biomass (primarily crop and forest residues) in the APEC region. That study estimated a similar volume of ethanol potential, 509 hm^3 of ethanol fuel or 245 Mt of gasoline equivalent, enough to displace two-fifths of the region's gasoline consumption and one-fifth of its crude oil import. Comparing the results from both studies at an economy level, it appears that some economies (such as China; Indonesia; Japan; Korea; Malaysia; the Philippines; Thailand; and Viet Nam) have large biomass potential from farm and forest residues, but limited potential from marginal lands (Appendix Tables 7 and 8). Other economies (Australia; Canada; Chile; Mexico; New Zealand; Russia; and United States) have major production potential on marginal lands as well as from residues. A combination of feedstock—lignocellulosic biomass from residues and biomass grown on marginal lands—would assure a sustainable resource supply for biofuels production in these economies. Such a supply could substantially displace current import and consumption of petroleum products.

The present study evaluates only the ethanol potential on marginal lands. Biodiesel could present very good opportunities for some of these lands in tropical regions, so future work should evaluate the biodiesel potential on marginal lands in APEC economies and compare it with the results from the previous study. More detailed assessments at a sub-regional or an economy level, and a finer than 100 km^2 spatial resolution, would also provide a better understanding of the biofuels potential on marginal lands in the APEC region. Given that the interest in biofuels is in large part driven by greenhouse gas mitigation policies, it would seem reasonable that future work be linked to climate modeling, which is now starting to have the ability to predict regional changes.

Introduction

Land is a precious commodity and more so today in the light of dynamic land use and land cover change driven by economic, environmental, social, and political factors. Availability of land to supply the emerging biofuels industry with enough biomass is a challenge shared by all APEC economies. In addition, the use of conventional crops for biofuels production has recently been of concern because they can compete with food materials. These considerations have encouraged the APEC economies to search for an alternative approach to biofuels feedstock supply—growing non-edible crops on marginal lands. Using these lands to grow energy crops, even though the lands are less productive, can provide some additional environmental and social benefits, including restoration of degraded land, carbon sequestration, and job creation.

Literature suggests that APEC economies have vast marginal lands available, which may hold potential for the production of biofuels feedstock. However, the term "marginal land" has been used quite loosely without a concrete definition. Moreover, in many economies, the extent and characteristics of marginal lands have not been systematically assessed, and their suitability for biofuels crop production has not been evaluated.

The goal of this study is to assess the biomass resource potential on marginal lands in the APEC region. To achieve this goal, the following two project objectives were defined:

1. Identify *available* marginal lands in the APEC economies and
2. Evalu*ate their* biomass production potential.

To accomplish the first objective, the project utilizes state of the art geographic information systems (GIS) technology—a computer-based information technology used to create, manipulate, analyze, and visualize geographic information. To accomplish the second objective, the study uses a crop production model that considers various inputs to simulate plant development.

This study intends to provide policy makers and industry developers with a general understanding of the biofuels potential on marginal lands in the APEC economies. It also aims to outline steps for further, more detailed analysis to guide their future strategic decisions.

Marginal Lands in APEC Economies

Definition of Marginal Lands

Marginal lands are characterized by poor climate, poor physical characteristics, or difficult cultivation. They include areas with limited rainfall, extreme temperatures, low quality soil, steep terrain, or other problems for agriculture. Examples include deserts, high mountains, land affected by salinity, waterlogged or marshy land, barren rocky areas, and glacial areas. Evidently, not all of these areas are suitable for agriculture. The authors evaluated various marginal land categories and identified the following as suitable for this study:

- Bare and herbaceous areas (not in use or with only moderately intensive pastoralism). Lands with intensive and extensive pastoralism are not included.
- Lands with moderate (8-16%) and steep (16-30%) slope.
- Lands with soil problems:
    - Shallow soils (depth < 50 cm)
    - Poorly and imperfectly drained soils
    - Soils with low to moderate natural fertility
    - Coarse textured or sandy soils (Arenosols, Regosols, and Vitric Andosols with coarse texture, and all soils with petric and stony phase)
    - Soils with heavy cracking clays (Vertisols and vertic sub-groups)
    - Salt-affected soils (Solonchaks, Solonetz, and Solodic Planosols)
    - Soils with gypsic horizon[1] (Gypsic Xerosols and Gypsic Yermosols)
    - Acid soils [pH is strongly (5.5 - 4.5) to extremely acid (<4.5)]
    - Soils with high calcium level or Calcisols
    - Peat soils (Histosols).

Data Information

Most of the marginal lands data for this study were obtained in a geospatial format from the Global Agro-Ecological Zones (GAEZ) system. The GAEZ program was developed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA). GAEZ evaluates climatic parameters, topography, soil, and land cover to estimate crop suitability and land productivity potentials for each 5-minute-latitude/longitude grid-cell (roughly each 10km x 10km or 100km^2 of land area) for the whole

[1] Gypsic soils are soils that contain sufficient quantities of gypsum (calcium sulphate).

world. This study uses soil constraints, climatic constraints, and topography datasets from GAEZ. Land use and dominant soils data (with the same spatial resolution of 100 km^2), as well as railroads and wetlands data, came from FAO's GeoNetwork, a geospatial data clearinghouse. Several datasets, such as Calcisols and land stress data, were provided by the United States Department of Agriculture. Data on protected areas were extracted from the World Database on Protected Areas, a joint product of the United Nations Environmental Program and the International Union for Conservation of Nature. Some reference data layers (administrative boundaries, cities, etc.) were obtained from the Environmental Systems Research Institute, while others (roads) were gathered from the Digital Chart of the World 1991-1992.

Analytic Methodology

To assess the *available* marginal lands in the APEC region, land use/cover and environmental exclusions have to be applied. These are areas where no conventional agriculture for food crops is recommended or possible. GIS technology is particularly useful for this type of analysis, considering the various tools it offers to support it. These tools include spatial overlay, intersection of data layers, and elimination of certain features. The marginal lands data were incorporated into the GIS system for spatial manipulation and analysis. The methodology for assessing the available marginal lands in APEC economies, using GIS, is illustrated in Figure 1.

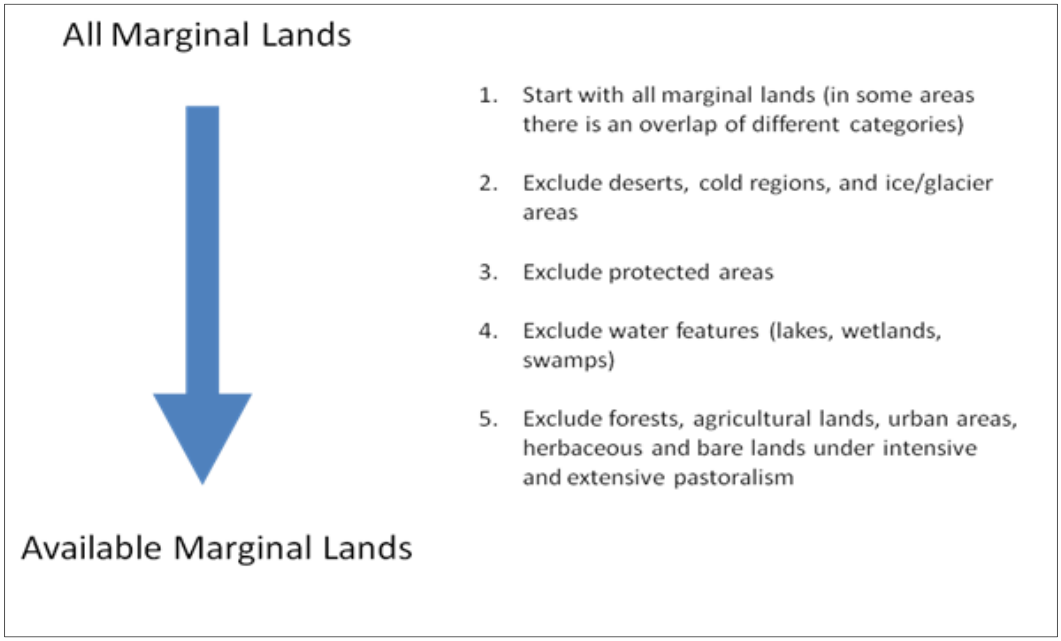

Figure 1 Methodology for Assessing Available Marginal Lands in APEC Economies

The results of this analysis are presented in both graphic and tabular format (Figure 2 and Table 1-2). The study estimates the available marginal lands in APEC economies at about 4 million km^2 or 6.5% of total land area. Economies with the largest total share of marginal lands include United States (13% of total land area); Australia (13.5%); China (5%); Canada (4%); and Russia (2%). Hong Kong and Singapore economies were excluded from this study due to their predominantly urban landscape, which would not be able to support crop development.

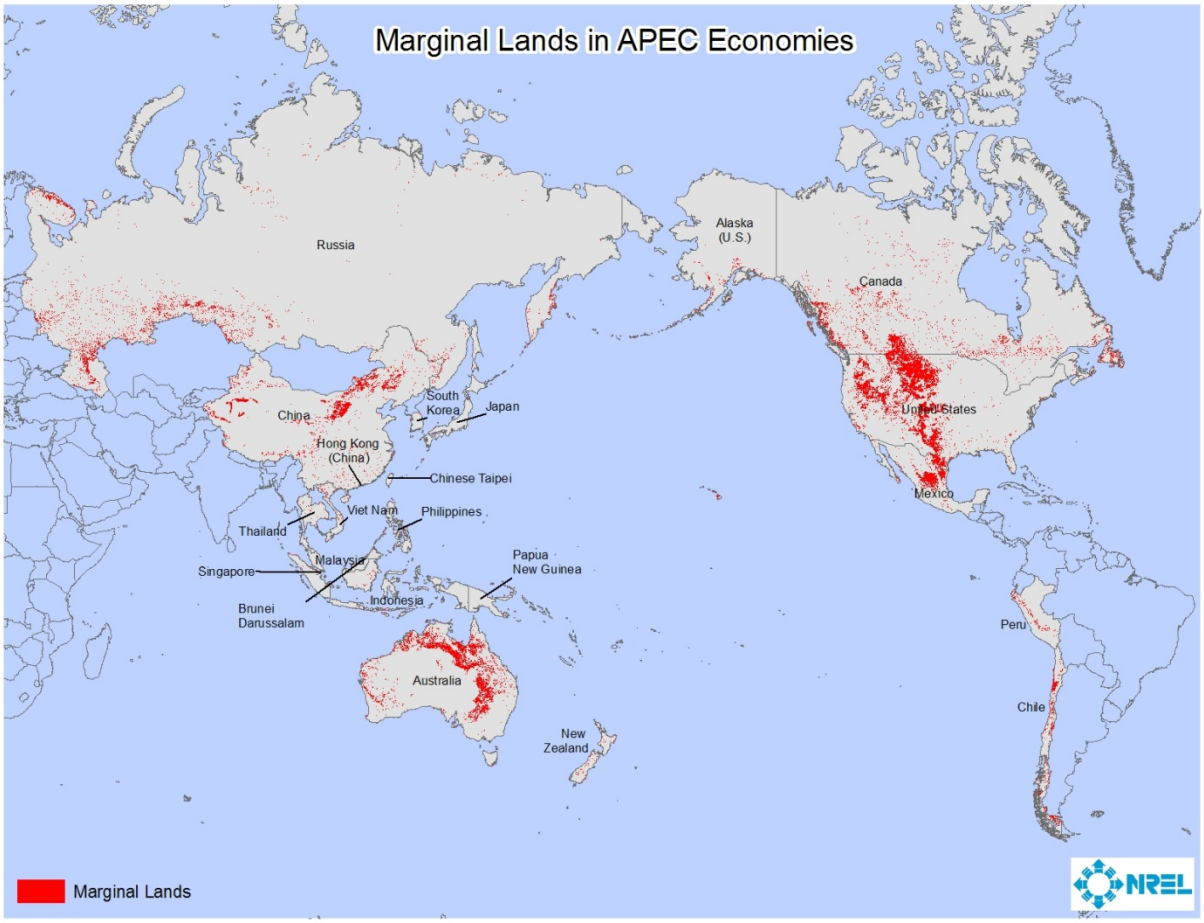

Figure 2 Marginal Lands in APEC Economies

Table 1 Marginal Lands in APEC Economies Part 1 of 2

Economy	Total Land Area (km^2)	Population 2007	Soils with High *Ca* Level (Calcids)		Soils with Heavy Cracking Clays		Shallow Soils		Poorly and Imperfectly Drained Soils		Soils with Low to Moderate Natural Fertility		Soils with Gypsic Horizon	
			km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Australia	7,694,273	20,434,176	70,928	0.9	250,966	3.3	147,240	1.9	77,473	1.0	377,322	4.9	0	0
Brunei	6,078	386,511	0	0	0	0	0	0	0	0	39	0.6	0	0
Canada	9,832,884	33,390,141	0	0	0	0	41,540	0.4	17,770	0.2	94,930	1.0	0	0
Chile	722,511	16,284,741	34	0.005	71	0.01	38,684	5.4	990	0.1	52,119	7.2	0	0
China	9,402,887	1,321,851,888	7,697	0.1	1,761	0.02	107,439	1.1	59,571	0.6	210,604	2.2	1,243	0.01
Indonesia	1,847,033	234,693,997	0	0	742	0.04	2,274	0.1	2,565	0.1	28,447	1.5	0	0
Japan	370,727	127,467,972	0	0	0	0	19	0.01	668	0.2	3,349	0.9	0	0
Korea	94,773	49,044,790	0	0	0	0	0	0	251	0.3	791	0.8	0	0
Malaysia	328,536	24,821,286	0	0	0	0	53	0.02	291	0.1	2,449	0.7	0	0
Mexico	1,953,851	108,700,891	22,739	1.2	35,344	1.8	129,414	6.6	3,633	0.2	49,685	2.5	0	0
New Zealand	267,214	4,115,771	0	0	0	0	150	0.1	1,162	0.4	12,174	4.6	0	0
PNG	458,666	5,795,887	0	0	0	0	543	0.1	138	0.03	4,739	1.0	0	0
Peru	1,296,605	28,674,757	0	0	1,776	0.1	26,373	2.0	2,729	0.2	33,038	2.5	0	0
Philippines	280,958	91,077,287	0	0	246	0.1	0	0	465	0.2	2,199	0.8	0	0
Russia	16,897,294	141,377,752	0	0	0	0	6,516	0.04	28,451	0.2	116,349	0.7	0	0
Chinese Taipei	35,980	22,858,872	0	0	0.007	0.00	355	1.0	250	0.7	236	0.7	0	0
Thailand	515,357	65,068,149	0	0	0	0	6,052	1.2	2,231	0.4	16,066	3.1	0	0
United States	9,426,295	301,139,947	18,771	0.2	22,118	0.2	77,612	0.8	20,510	0.2	98,960	1.0	0	0
Viet Nam	322,743	85,262,356	0	0	232	0.1	11,056	3.4	645	0.2	19,226	6.0	0	0
Total	61,754,665	2,682,447,171	120,169	0.2	313,256	0.5	595,319	1.0	219,792	0.4	1,122,724	1.8	1,243	0.002

Table 2 Marginal Lands in APEC Economies Part 2 of 2

Economy	Total Land Area (km^2)	Population 2007	Histosols		Salt-affected Soils		Acid Soils		Coarse-textured Soils or Sandy Soils		Lands with Moderate and Steep Slopes		Select Land Use Categories		Total Marginal Lands	
			km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Australia	7,694,273	20,434,176	0	0	580,712	7.5	29,255	0.4	114,506	1.5	31,907	0.4	1,024,020	13.3	1,036,239	13.5
Brunei	6,078	386,511	0.18	0.003	1	0.01	28	0.5	0	0	0	0	39	0.6	85	1.4
Canada	9,832,884	33,390,141	27,625	0.3	20,546	0.2	208,606	2.1	6,546	0.07	91,550	0.9	368,550	3.7	376,092	3.8
Chile	722,511	16,284,741	490	0.1	4,609	0.6	12,234	1.7	1,047	0.1	41,562	5.8	91,191	12.6	95,645	13.2
China	9,402,887	1,321,851,888	939	0.01	72,859	0.8	143,893	1.5	0	0	207,575	2.2	507,174	5.4	511,905	5.4
Indonesia	1,847,033	234,693,997	3,397	0.2	270	0.01	19,057	1.0	3,086	0.2	14,247	0.8	17,548	1.0	37,123	2.0
Japan	370,727	127,467,972	0	0	0	0	1,889	0.5	0	0	3,331	0.9	93	0.03	4,878	1.3
Korea	94,773	49,044,790	0	0	0	0	632	0.7	0	0	902	1.0	263	0.3	1,651	1.7
Malaysia	328,536	24,821,286	686	0.2	968	0.3	1,737	0.5	113	0.03	1,204	0.4	828	0.3	3,534	1.1
Mexico	1,953,851	108,700,891	0	0	76,789	3.9	902	0.0	18,771	1.0	134,347	6.9	252,140	12.9	255,862	13.1
New Zealand	267,214	4,115,771	24	0.01	58	0.02	4,161	1.6	1,112	0.4	7,474	2.8	13,315	5.0	17,299	6.5
PNG	458,666	5,795,887	229	0.05	30	0.01	426	0.1	0	0	3,875	0.8	103	0.02	7,123	1.6
Peru	1,296,605	28,674,757	0	0	1,660	0.1	4,447	0.3	8,508	0.7	16,638	1.3	56,810	4.4	57,029	4.4
Philippines	280,958	91,077,287	0	0	303	0.1	2,536	0.9	35	0.01	4,122	1.5	864	0.3	6,357	2.3
Russia	16,897,294	141,377,752	13,849	0.1	47,339	0.3	52,187	0.3	1,881	0.01	99,485	0.6	361,173	2.1	369,176	2.2
Chinese Taipei	35,980	22,858,872	0	0	94	0.3	250	0.7	0	0	54	0.1	316	0.9	693	1.9
Thailand	515,357	65,068,149	0.05	0.00	289	0.1	14,904	2.9	320	0.06	8,177	1.6	15,893	3.1	17,253	3.3
United States	9,426,295	301,139,947	962	0.01	424,042	4.5	39,258	0.4	206,941	2.2	659,996	7.0	1,207,300	12.8	1,214,007	12.9
Viet Nam	322,743	85,262,356	0.05	0.00	299	0.1	18,020	5.6	400	0.1	8,729	2.7	19,432	6.0	21,090	6.5
Total	61,754,665	2,682,447,171	48,201	0.1	1,230,868	2.0	554,423	0.9	363,265	0.6	1,335,174	2.2	3,937,054	6.4	4,033,039	6.5

Select land use categories include bare and herbaceous areas (not in use or with only moderately intensive pastoralism). It doesn't include lands with intensive and extensive pastoralism. Total marginal lands don't correspond to the sum of all categories due to geographic overlap among land types.

Biomass Potential on Marginal Lands in APEC Economies

The prediction of crop yields in farm systems and of the net rate of carbon fixation by the biosphere has become very important as humanity attempts to balance the needs of society against the maintenance of the ecosystems that support life on the planet. Using the benefits of crop growth simulation and GIS techniques, this study estimates the potential yield of energy crops on marginal lands that are either abandoned or not used in mainstream agriculture, due to either economic or environmental challenges.

Crop yields have been estimated for the last 50 years, though significant advances did not really appear until the widespread availability of satellite sensor data after the 1970s. The initial estimation methods grew out of the development of crop growth models, which attempted to relate plant physiology to the seasonal growing conditions and the optimization of the growth parameters. Major contributions to this field were made at the University of Wageningen in the Netherlands. There, in the 1970s, Professor C.T. de Wit established academic courses addressing both simulation techniques and the mechanisms of crop physiology (Goudriaan, J. and H. H. van Laar 1994).

At the time, simulation techniques were in their infancy, but crop physiology had by then established the major features of the control of plant yield. In order of importance, these are (1) the energy input determined by both the supply of solar radiation and the radiation use efficiency (RUE), (2) water availability, measured by water vapor pressure which is a product of the physics of water transport in the plant and the nature of the stomatal openings[2] in the leaf that let CO_2 in, and (3) nutrient availability, especially nitrogen, which is needed to produce the nucleic acids, DNA and protein of the plant and its seeds.

The RUE is typically 1 – 2 g of dry matter production per MJ of light intercepted. If the plant has an extensive area of leaf coverage, i.e. a Leaf Area Index (LAI) of 4 m^2 of leaf surface per m^2 of land area, the daily dry matter accumulation at 12 MJ/m^2 irradiation will be about 20 g/m^2/day. Over a 100 day growing season at this rate, the harvestable above-ground biomass will be 20 t/ha (20 g/m^2/day x 100 x 10^4 m^2/ha x 10^{-6} t/g). This assumes that there is no water deficit or

[2] In botany, a stoma is a pore, found in the leaf and stem epidermis that is used for gas exchange.

nutrient limitation. At around 500+ mm of water per year evenly distributed in the growing season, this is usually the case.

In parallel with the work on crop growth simulation and with fundamental studies in photosynthesis, the International Geophysical Year of 1965 saw the first integrated perspectives on how the entire biosphere interacts with the atmosphere and indirectly with the oceans through the carbon dioxide (CO_2) cycle. This work also became more important as there was growing awareness of how changes in the greenhouse gases (GHG) levels in the atmosphere were likely to alter the climate. The climate work of course is focused on the two most important GHG (CO_2 and water vapor) and their interaction with the biosphere with respect to the net flow of carbon from the atmosphere to the plant biomass and the stability of these processes with respect to maintaining the atmosphere in equilibrium. Climate modeling increased the investment in this area significantly and the high priority of the topic led to the addition of much more detailed mapping and the application of GIS to interpret the data.

The energy crops of the future are not yet known. There is a general concern that the use of food crops could conflict with the supply of food and animal feed for the growing human population. It is also recognized that crops for energy may have to meet more stringent sustainability criteria than existing food and feed crops. Obviously both the food and the energy crop systems have to be sustainable. However, there is already a burden of proof in some jurisdictions that energy crop systems should be capable of offsetting fossil carbon emissions by more than half. Criteria for sustainable carbon offset are being developed by the U.S. Environmental Protection Agency and required by Directive 2009/28/EC of the European Parliament.

Carbon displacement and net energy efficiency are measured using the tools of life cycle assessment (LCA) in what are often described as well-to-wheel (WTW) analyses. Because energy crops are used for heat, combined heat and power (CHP), electricity, and synthetic natural gas (SNG), as well as liquid fuels for transportation, this project uses the results from full LCA, rather than just WTW analysis, to describe the assessment of the energy crop cycles in determining the optimum crop and product strategy.

LCA has identified several important criteria for an energy crop. Perhaps the most basic criterion is that the energy yield has to be high (i.e. the solar energy captured in the biomass

has to be maximized). Obviously the harvested energy crop obviously has to have characteristics that are suitable for the envisioned end use. For thermal energy applications, the maximum yield criterion suggests that lignocellulosics such as wood and herbaceous species would give the highest yield, as these are closest in chemical composition to the photosynthate produced in the leaf and thus minimize transformation losses inside the growing grass or tree species. For liquid transportation biofuels, volumetric energy density is important. Such fuels as ethanol and biodiesel are more reduced than the simple photosynthate, and there is competition between plants that naturally produce hydrocarbons such as waxes, lipids, or triacylglycerides (TAG) and the use of industrial processes in chemical plants or biorefineries to convert lignocellulosics, starches, and sugars into the final product. LCAs also suggest that the plants should be perennials to avoid the energy and material costs of an annual cycle of tillage, planting (of seeds or cuttings), tending, and harvesting. Likewise, the issue of tillage and the loss of soil carbon is an important criterion in crop evaluation.

Another important criterion is the issue of land use change (LUC), which has two facets that are called direct and indirect. Direct LUC is the change in status of the area that was previously in either a crop or abandoned land, to an energy crop. The other concern is of indirect LUC as it is argued that increasing land in energy crops will require that food cultivation will have to be increased elsewhere, either by converting other land into agricultural (food) production, intensifying existing land use for food, or reducing human food consumption. The measurement of indirect LUC is complex and is being strongly debated. At a minimum understanding, this issue will require complex economic models of world food production linked to the energy system.

Land clearing and preparation for planting, as well as tillage, will cause carbon fixed in the soil to be released, possibly creating a deficit in carbon balance that will need to be repaid by the fossil energy displacement of the energy crop in order for biofuels production to be environmentally sustainable. This deficit can be just one year or less for the cultivation of marginal lands, as well as for most cropland under cultivation and for many types of grassland. But it is substantially greater, typically in the order of a few decades, when woody savanna or secondary or degraded forest is involved, and it can range up to several centuries for most tropical forest or even several millennia for tropical peat forest. Hence, the development of energy crops on marginal lands, provided that they are reasonably productive, has a major

advantage over development of these crops on croplands from the standpoint of carbon impacts of direct land use change.

A number of candidate energy crops are being tested around the world. Many are lignocellulosic crops including tree species such as poplar, willow, and eucalyptus and herbaceous crops such as switchgrass and Miscanthus. Oil bearing shrubs and trees such as *Jatropha Curcas* and Pongamia are examples of *in planta* biochemical conversions to biofuel precursors as their seeds provide TAG for processing into diesel fuels such as fatty acid methyl esters or renewable diesel.

Because of the diversity of potential energy crops and their evolving sustainability criteria, we have chosen to provide an estimate of the productivity of potential bioenergy crop lands in terms of the annual Net Primary Productivity or NPP. Readers can then choose their own crop and factor in its allocation of NPP carbon into the energy crop product that they need— be it branches and above ground stem for lignocellulosic or the TAG yield for an oil crop. The annual NPP values are a valuable indicator of the optimum locations within the available land classes for further investigation.

In order to explain the process used, we will first discuss crop modeling as this is the foundation of estimating the NPP. We will then explain how we have brought into the NPP assessment the GIS information on actual vegetation cover status to more accurately reflect the actual site potential.

Plant Growth Modeling

The seminal work of the University of Wageningen has been widely adopted around the world in crop production modeling, and a relatively simple model SUCROS is described below that elucidates how crop modeling proceeds. The general outline of SUCROS-like models is illustrated in Figure 3. Flows of energy and material (solid lines with arrows) as well as control signals (dotted) are illustrated.

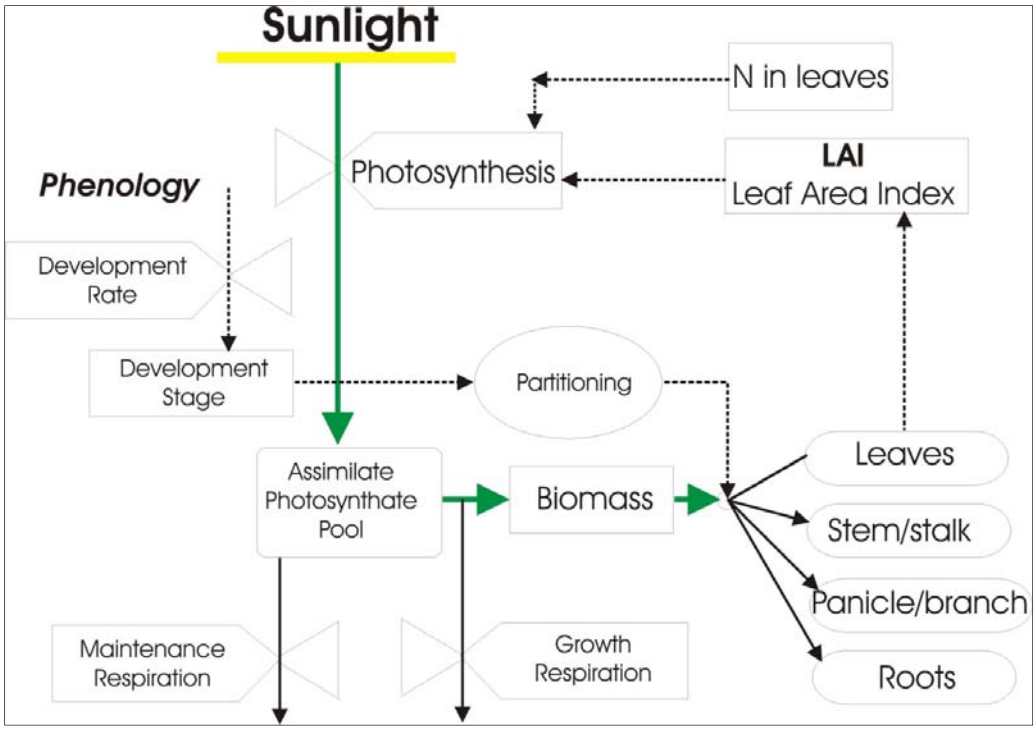

Figure 3 General Outline of Crop Production Modeling

The key physiological inputs required for the simulation of crop growth, such as Leaf Area Index, are available for many crop species. The crop growth pattern is called the phenology of the plant and identifies the different stages of growth pattern with energy and time input over the growing season. Time and energy are interlinked and the phenology in the field can be tracked against daily heat units, a crude measure of the average daily temperature. For example, to produce a mature winter wheat variety, about 2,200 daily heat units are required. This means that it would take 147 calendar days to produce a winter wheat crop if the average daily temperature was a constant 15°C. In the early stages, the plant develops leaves and more stems (tillers). As the leaves develop, more energy is intercepted and the wheat moves through to so-called boot development, which leads to flowering and then the filling of the grain.

The other part of SUCROS is the incorporation of actual weather data for the growing site. This determines the energy input as solar energy on an hourly and daily basis which is then used to calculate the assimilation of CO_2. The assimilated CO_2 is then passed as photosynthate to carbohydrate production (photosynthate = CH_2O, the monomer of carbohydrates), which in turn passes into a module for dry matter partitioning between the various plant components. Part of the photosynthate is consumed in “powering” the growth and transport processes. This is called

maintenance respiration. This factor is very temperature-dependent and accounts for the poor performance of plant species at high temperatures.

The descendents of SUCROS for the estimation of crop yields then require extensive weather data records for the solar input, temperature, and rainfall. They also require knowledge of the soil properties, particularly with respect to water-holding properties. And, as described above, they require a detailed phenological[3] development of the chosen species/cultivar. Such process models have been extensively developed for U.S. agriculture. These models are currently in their third decade. CENTURY (and its sibling DayCent, a daily version) originated at the Colorado State University's Natural Resources Ecology Laboratory in the 1980s with National Science Foundation funding and U.S. Department of Agriculture support. Many versions later, William J. Parton continues to lead its development into the biogeochemical behavior of carbon, nitrogen, phosphorus and sulphur in the arable crop environment, as well as grasslands, savanna, and forests. The European model WOFOST is a direct descendent of SUCROS and has been further developed by the Joint Research Centre of the European Commission to predict current annual crop yields and compare them with historical data to determine trends related to climate change. Information on these and many more models can be found on the Register of Ecological Models maintained by Ecobas.org.

As the need for modeling has moved away from crops about which detailed phenology is available and into regions of the world without detailed time series weather data, the general principles described above have been adapted. In some instances, the need to grow known crops in new locations has been met by means of synthetic climate generators. Given some inputs and possibly GIS data obtained by Satellite, stochastic time series can be generated for a given location for input into the models. Likewise, the all important solar input can now be calculated at any point on the surface of the globe using tools developed by the U.S. National Aeronautics and Space Administration and the U.S. Department of Energy's National Renewable Energy Laboratory.

We have chosen to use data generated by a combined model by VITO (Flemish Institute for Technological Research). This model is primarily based on radiation with satellite sensor data for the fraction of the photosynthetically active radiation (PAR) absorbed at a given location. The

[3] Phenology is the scientific study of periodic biological phenomena, such as flowering, breeding, and migration, in relation to climatic conditions.

model is used with SPOT satellite images and National Oceanic and Atmospheric Administration data at a 1 km^2 pixel resolution to provide 10 day average values of NPP starting on the 1st, 10th, and 21st day of each month. To generate the NPP for an entire year, the 36 sets of data are combined to give an annual value. The process used calculates three values:

Gross Primary Productivity: GPPd = *f*APARd **.** ε **.** CO_2*fert* **.** *pa (Td)***.** c **.**Sgd (1)

Net Primary Productivity: NPPd = GPPd**.** (1 - Ad) (2)

Net Ecosystem Productivity: NEPd = NPPd - Rd = NPPd - ky **.** *ph (Td)* (3)

In Equation 1, the daily flux of carbon captured by photosynthesis in g/m^2/day is based on the Montief method, developed by Phillippe Montief in the late 1880s. Sgd is the daily incoming global solar radiation (MJ/m^2/day) calculated from a solar irradiance model. This is multiplied by "c," a factor of 0.48 which is the fixed proportion of PAR between 400 – 700 nm. GPP is also dependent on the air temperature (average daily value Td), a non-linear effect captured by the term *pa (Td)*. The CO_2 fertilization factor, *CO_2fert*, computes the effect of the increasing CO_2 levels on the performance of the enzyme Rubisco which captures the CO_2 in the plant leaf. *f*APARd is the fraction of PAR captured in the canopy, which is based on the relation between this and the Normalized Difference Vegetation Index (NDVI) derived from the satellite based remote sensing. The term ε is the previously described radiation use efficiency (RUE) which is fixed in this model as 1.1 g of carbon mass in biomass per MJ of insolation.

Equation 2 calculates NPP by adjusting for the respiration that takes place in the plant and returns carbon to the atmosphere. This is portrayed in the model by a linear dependence on the air temperature (Veroustraete F. and Sabbe H. 2000).

We do not use the third equation in this study, as it concerns the annual carbon flux and calculates the return of carbon from the soil at the end of the growing cycle. Clearly this is important in the calculation of the carbon flux from the atmosphere to the ecosystems of the world. In our case, however, the key carbon flux is the harvest of biomass for use as either bioenergy or as feedstock for the production of biofuels.

NPP as carbon uptake on an annual basis was measured for the growth year 1999-2000 at a spatial resolution of 100km^2 grid-cell using GeoSuccess data (VITO 2009). Data for the Northern Hemisphere were for the calendar year 1999, while those for the Southern Hemisphere were

taken from June 1999 through May 2000. Ideally, the average of several years should be taken into account, but for this project it was only possible to take this single annual snapshot.

The marginal lands' productivity in APEC economies is illustrated in Figure 4. The range of NPP values run from zero (no carbon capture) to values greater than 20 t/ha/yr. As can be seen, the marginal lands in APEC economies have low productivity. The predominant NPP value is less than 6 t/ha/yr. The values are indicative in that they are a single value shown at a 100 km^2 grid-cell for the terrestrial carbon flux as NPP. An additional uncertainty is that the data are calculated for a RUE of 1.1 g/MJ. Plant breeding has improved this value to almost 2 g/MJ in crops such as sugarcane growing under high-input irrigated conditions, but such conditions might not be typical on marginal lands (Sinclair, T.R., Muchow, R.C.1999).

The results are presented in terms of the mass of carbon fixed by the plants. However, biomass can also be estimated in terms of harvestable above-ground lignocellulosics. This is done by multiplying the carbon value by 1.25—going from carbon to lignocellulosic mass—and assuming that one third of the biomass is below ground and non recoverable[4]. Tables 3 and 4 present the biomass resource potential on marginal lands in APEC economies, as well as the associated biofuels potential. The NPP values are aggregated to country level using standard GIS techniques, considering the marginal land hectares in each 100 km^2 cell and the NPP per hectare associated with individual cells. Economies with the highest biomass resource potential include Australia; United States; Russia; China; and Canada due to their large marginal land areas. But such economies vary significantly in terms of their biomass yield per unit of area and thus in the portion of the potential that can be practically obtained.

[4] NPP measured as carbon includes both above- and below-ground biomass. We assumed from the literature that the above-ground is 2/3 of the total carbon fixed. The chemical formula of lignocellulosic biomass, averaged across many species, is somewhere around $CH^{1.4}$ $O^{0.56}$. In other words, 1.4 hydrogen atoms (with a mass of 1) and 0.56 oxygen atoms (with a mass of 16) for each atom of carbon (with a mass of 12). Therefore, the total molecular weight of a typical lignocellulosic feedstock, relative to an atom of carbon, is (1.4x1 + 0.56x16 + 1x12) / 12 or about 22.5 / 12 or 1.88. Multiplying this ratio of lignocellulose to carbon, 1.88, by the portion of carbon above ground, 2/3, we find that the ratio of lignocellulose to total carbon is 1.88 x 2/3 = 1.25

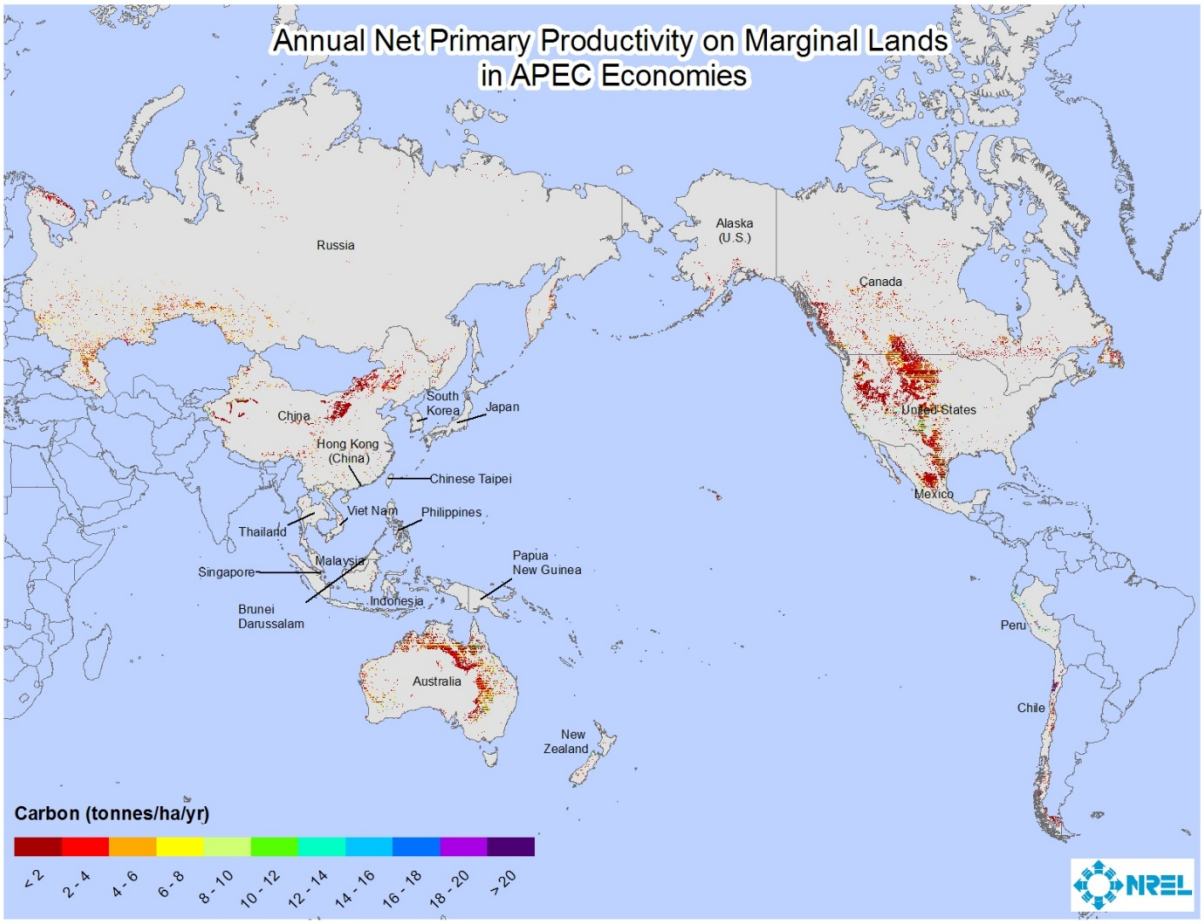

Figure 4 Annual Net Primary Productivity on Marginal Lands in APEC Economies

IIASA, in their studies of the European land potential, have classified area yields of biomass as follows: Very Suitable (VS) 13 – 17 t/ha; Suitable (S) 10 – 13 t/ha; Moderately Suitable (MS) 7 – 10 t/ha; marginally suitable (ms) 3-5 t/ha; and Not Suitable (NS) less than 2 t/ha. The classification incorporates economic principles that relate to harvesting effort and the necessary radius of collection, as the harvested areas increase rapidly with decreasing productivity and suitability classification. The gold standard, which energy crops such as switchgrass or tree species are hoped to reach, has already been demonstrated in trials with yields of 23 – 27 t/ha of lignocellulosic biomass on good land with adequate rainfall and a long growing season (BRDB 2008).

Table 3 Marginal Lands Productivity in APEC Economies Part 1 of 2

Economy	Soils with High *Ca* Level (Calcids)				Soils with Heavy Cracking Clays				Shallow Soils			
	km^2	NPP (tonne/yr)	Biomass (tonne/yr)	Biofuels (hm^3)	km^2	NPP (tonnes/yr)	Biomass (tonnes/yr)	Biofuels (hm^3)	km^2	NPP (tonnes/yr)	Biomass (tonnes/yr)	Biofuels (hm^3)
Australia	70,928	21,792,987	27,328,405	10.7	250,966	57,299,465	71,853,529	28.2	147,240	41,625,810	52,198,765	20.5
Brunei	0	0	0	0	0	0	0	0	0	0	0	0
Canada	0	0	0	0	0	0	0	0	41,540	8,968,876	11,246,971	4.4
Chile	34	3,613	4,531	0.002	71	64,694	81,126	0.0	38,684	12,221,208	15,325,395	6.0
China	7,697	57,863	72,560	0.029	1,761	701,211	879,318	0.3	107,439	26,007,893	32,613,898	12.8
Indonesia	0	0	0	0	742	166,053	208,231	0.1	2,274	670,079	840,279	0.3
Japan	0	0	0	0	0	0	0	0	19	15,101	18,937	0.007
Korea	0	0	0	0	0	0	0	0	0	0	0	0
Malaysia	0	0	0	0	0	0	0	0	53	865	1,085	0.0004
Mexico	22,739	2,068,538	2,593,946	1.019	35,344	9,479,353	11,887,109	4.7	129,414	28,089,120	35,223,756	13.8
New Zealand	0	0	0	0	0	0	0	0	150	74,958	93,997	0.04
PNG	0	0	0	0	0	0	0	0	543	81,021	101,600	0.04
Peru	0	0	0	0	1,776	2,114,334	2,651,375	1.0	26,373	21,116,598	26,480,213	10.4
Philippines	0	0	0	0	246	192	241	0.0	0	0	0	0
Russia	0	0	0	0	0	0	0	0	6,516	2,034,340	2,551,062	1.0
Chinese Taipei	0	0	0	0	0.007	8	10	0.0	355	376,145	471,685	0.2
Thailand	0	0	0	0	0	0	0	0	6,052	2,692,007	3,375,777	1.3
United States	18,771	4,238,290	5,314,815	2.088	22,118	6,197,593	7,771,781	3.1	77,612	24,623,345	30,877,675	12.1
Viet Nam	0	0	0	0	232	60,100	75,365	0.0	11,056	5,471,106	6,860,767	2.7
Total	120,169	28,161,291	35,314,258	13.877	313,256	76,083,003	95,408,085	37.5	595,319	174,068,471	218,281,863	85.8

Economy	Poorly and Imperfectly Drained Soils				Soils with Low to Moderate Natural Fertility				Soils with Gypsic Horizon			
	km^2	NPP (tonnes/yr)	Biomass (tonnes/yr)	Biofuels (hm^3)	km^2	NPP (tonnes/yr)	Biomass (tonnes/yr)	Biofuels (hm^3)	km^2	NPP (tonnes/yr)	Biomass (tonnes/yr)	Biofuels (hm^3)
Australia	77,473	27,336,623	34,280,125	13.5	377,322	119,636,665	150,024,378	59.0	0	0	0	0
Brunei	0	0	0	0	39	8,529	10,695	0.004	0	0	0	0
Canada	17,770	4,664,255	5,848,976	2.3	94,930	22,928,849	28,752,777	11.3	0	0	0	0
Chile	990	85,258	106,914	0.04	52,119	16,186,530	20,297,908	8.0	0	0	0	0
China	59,571	12,362,702	15,502,829	6.1	210,604	49,639,536	62,247,978	24.5	1,243	66,976	83,987	0.03
Indonesia	2,565	1,049,924	1,316,605	0.5	28,447	9,561,810	11,990,510	4.7	0	0	0	0
Japan	668	148,812	186,610	0.1	3,349	1,142,390	1,432,558	0.6	0	0	0	0
Korea	251	63,007	79,011	0.03	791	221,956	278,333	0.1	0	0	0	0
Malaysia	291	13,255	16,621	0.01	2,449	689,762	864,962	0.3	0	0	0	0
Mexico	3,633	811,148	1,017,179	0.4	49,685	16,055,320	20,133,371	7.9	0	0	0	0
New Zealand	1,162	455,045	570,626	0.2	12,174	5,452,492	6,837,425	2.7	0	0	0	0
PNG	138	0	0	0	4,739	826,008	1,035,814	0.4	0	0	0	0
Peru	2,729	2,478,509	3,108,050	1.2	33,038	27,413,672	34,376,745	13.5	0	0	0	0
Philippines	465	51	64	0.0	2,199	468,360	587,324	0.2	0	0	0	0
Russia	28,451	8,802,016	11,037,728	4.3	116,349	40,282,191	50,513,868	19.8	0	0	0	0
Chinese Taipei	250	48,467	60,778	0.02	236	143,914	180,469	0.1	0	0	0	0
Thailand	2,231	1,132,567	1,420,240	0.6	16,066	7,696,834	9,651,830	3.8	0	0	0	0
United States	20,510	6,306,651	7,908,541	3.1	98,960	32,557,662	40,827,308	16.0	0	0	0	0
Viet Nam	645	228,157	286,109	0.1	19,226	8,566,362	10,742,218	4.2	0	0	0	0
Total	219,792	65,986,448	82,747,005	32.5	1,122,724	359,478,845	450,786,471	177.1	1,243	66,976	83,987	0.03

Table 4 Marginal Lands Productivity in APEC Economies Part 2 of 2

Economy	Histosols				Salt-affected Soils				Acid Soils			
	km^2	NPP (tonnes/yr)	Biomass (tonnes/yr)	Biofuels (hm^3)	km^2	NPP (tonnes/yr)	Biomass (tonnes/yr)	Biofuels (hm^3)	km^2	NPP (tonnes/yr)	Biomass (tonnes/yr)	Biofuels (hm^3)
Australia	0	0	0	0	580,712	165,507,795	207,546,775	81.6	29,255	10,837,735	13,590,520	5.3
Brunei	0.18	22	28	0.0	1	476	597	0.0	28	498	625	0.0
Canada	27,625	5,619,826	7,047,261	2.8	20,546	4,408,403	5,528,137	2.2	208,606	48,217,685	60,464,977	23.8
Chile	490	24,763	31,053	0.01	4,609	1,639,344	2,055,738	0.8	12,234	1,717,654	2,153,938	0.8
China	939	245,253	307,547	0.1	72,859	6,910,797	8,666,140	3.4	143,893	36,908,980	46,283,861	18.2
Indonesia	3,397	1,256,146	1,575,208	0.6	270	86,128	108,004	0.04	19,057	7,055,273	8,847,312	3.5
Japan	0	0	0	0	0	0	0	0	1,889	720,126	903,039	0.4
Korea	0	0	0	0	0	0	0	0	632	161,379	202,370	0.1
Malaysia	686	302,628	379,495	0.1	968	163,394	204,897	0.1	1,737	502,813	630,527	0.2
Mexico	0	0	0	0	76,789	11,832,631	14,838,120	5.8	902	242,533	304,136	0.1
New Zealand	24	0	0	0	58	49,275	61,791	0.02	4,161	2,774,851	3,479,663	1.4
PNG	229	25,979	32,577	0.01	30	5,058	6,343	0.002	426	108,412	135,949	0.1
Peru	0	0	0	0	1,660	1,963,060	2,461,677	1.0	4,447	3,468,980	4,350,101	1.7
Philippines	0	0	0	0	303	18,369	23,035	0.009	2,536	681,201	854,226	0.3
Russia	13,849	4,578,647	5,741,623	2.3	47,339	15,343,205	19,240,379	7.6	52,187	14,825,645	18,591,359	7.3
Chinese Taipei	0	0	0	0	94	40,253	50,478	0.02	250	276,025	346,135	0.1
Thailand	0.05	0	0	0	289	139,559	175,007	0.1	14,904	7,254,768	9,097,479	3.6
United States	962	214,902	269,487	0.1	424,042	104,996,892	131,666,102	51.7	39,258	13,491,125	16,917,870	6.6
Viet Nam	0.05	17	21	0.0	299	48,584	60,925	0.02	18,020	7,918,315	9,929,567	3.9
Total	48,201	12,268,181	15,384,300	6.0	1,230,868	313,153,225	392,694,144	154.3	554,423	157,163,997	197,083,652	77.4

Economy	Coarse-textured Soils or Sandy Soils				Lands with Moderate and Steep Slopes			
	km^2	NPP (tonnes/yr)	Biomass (tonnes/yr)	Biofuels (hm^3)	km^2	NPP (tonnes/yr)	Biomass (tonnes/yr)	Biofuels (hm^3)
Australia	114,506	35,111,479	44,029,794	17.3	31,907	13,668,677	17,140,521	6.7
Brunei	0	0	0	0	0	0	0	0
Canada	6,546	789,855	990,479	0.4	91,550	22,672,981	28,431,918	11.2
Chile	1,047	261,532	327,961	0.1	41,562	15,471,411	19,401,150	7.6
China	0	0	0	0	207,575	33,278,956	41,731,810	16.4
Indonesia	3,086	1,456,617	1,826,598	0.7	14,247	4,984,612	6,250,703	2.5
Japan	0	0	0	0	3,331	939,402	1,178,010	0.5
Korea	0	0	0	0	902	229,197	287,413	0.1
Malaysia	113	22,197	27,835	0.01	1,204	318,187	399,006	0.2
Mexico	18,771	6,362,397	7,978,445	3.1	134,347	27,231,532	34,148,341	13.4
New Zealand	1,112	718,153	900,563	0.4	7,474	4,272,210	5,357,351	2.1
PNG	0	0	0	0	3,875	582,506	730,462	0.3
Peru	8,508	7,782,536	9,759,300	3.8	16,638	15,731,566	19,727,384	7.8
Philippines	35	14,031	17,594	0.01	4,122	977,571	1,225,874	0.5
Russia	1,881	613,132	768,868	0.3	99,485	29,851,940	37,434,332	14.7
Chinese Taipei	0	0	0	0	54	59,281	74,339	0.03
Thailand	320	144,060	180,651	0.1	8,177	4,208,768	5,277,795	2.1
United States	206,941	53,026,621	66,495,383	26.1	659,996	151,106,644	189,487,731	74.5
Viet Nam	400	37,522	47,053	0.02	8,729	3,037,383	3,808,878	1.5
Total	363,265	106,340,132	133,350,525	52.4	1,335,174	328,622,822	412,093,019	161.9

Economy	Select Land Use Categories				Total Marginal Lands			
	km^2	NPP (tonnes/yr)	Biomass (tonnes/yr)	Biofuels (hm^3)	km^2	NPP (tonnes/yr)	Biomass (tonnes/yr)	Biofuels (hm^3)
Australia	1,024,020	307,891,525	386,095,972	151.7	1,036,239	310,657,103	389,564,007	153.1
Brunei	39	0	0	0	85	8,551	10,723	0.004
Canada	368,550	73,402,554	92,046,803	36.2	376,092	78,565,045	98,520,566	38.7
Chile	91,191	30,537,053	38,293,465	15.0	95,645	31,195,809	39,119,545	15.4
China	507,174	96,597,179	121,132,862	47.6	511,905	97,861,854	122,718,765	48.2
Indonesia	17,548	6,887,067	8,636,381	3.4	37,123	12,356,024	15,494,454	6.1
Japan	93	9,261	11,613	0.005	4,878	1,534,099	1,923,760	0.8
Korea	263	86,915	108,992	0.04	1,651	468,861	587,952	0.2
Malaysia	828	424,004	531,701	0.2	3,534	838,999	1,052,105	0.4
Mexico	252,140	51,640,420	64,757,087	25.4	255,862	55,023,788	68,999,830	27.1
New Zealand	13,315	5,551,773	6,961,923	2.7	17,299	7,654,439	9,598,667	3.8
PNG	103	98,307	123,277	0.05	7,123	1,142,311	1,432,459	0.6
Peru	56,810	52,588,924	65,946,511	25.9	57,029	52,811,344	66,225,425	26.0
Philippines	864	269,192	337,567	0.1	6,357	1,429,437	1,792,514	0.7
Russia	361,173	121,248,424	152,045,524	59.7	369,176	123,135,555	154,411,986	60.7
Chinese Taipei	316	339,520	425,758	0.2	693	444,666	557,611	0.2
Thailand	15,893	7,717,068	9,677,204	3.8	17,253	8,289,020	10,394,431	4.1
United States	1,207,300	285,249,782	357,703,227	140.6	1,214,007	300,966,979	377,412,592	148.3
Viet Nam	19,432	8,755,088	10,978,881	4.3	21,090	8,995,711	11,280,622	4.4
Total	3,937,054	1,049,294,057	1,315,814,748	517.1	4,033,039	1,093,379,598	1,371,098,016	538.8

NPP – Net Primary Productivity (carbon); conversion of NPP to above ground biomass that can be harvested: multiply by 1.25; biomass conversion to volume: assumed that the overall process is 45% thermal efficiency to an ethanol liquid fuel with an energy density of 27 MJ/kg and a physical density of 789 kg m^3

Taking the average productivity across the entire individual APEC economy, while ignoring possible hot spots of better potential, and applying IIASA's classification of land suitability described above, Table 5 illustrates that marginal lands are indeed marginal with respect to biofuels feedstock potential.

Table 5 Average Biofuels Potential on Marginal Lands in APEC Economies

Economy	Marginal Lands (km^2)	Biofuels Potential (hm^3)	Biofuels Density (m^3/ha)	Biomass Yield (t/ha)*	Suitability Class
Australia	1,036,239	153.1	1.5	3.8	ms
Brunei	85	0.004	0.5	1.3	NS
Canada	376,092	38.7	1.0	2.6	ms
Chile	95,645	15.4	1.6	4.1	ms
China	511,905	48.2	0.9	2.4	NS
Indonesia	37,123	6.1	1.6	4.2	ms
Japan	4,878	0.8	1.5	4.0	ms
Korea	1,651	0.2	1.4	3.6	ms
Malaysia	3,534	0.4	1.2	3.0	ms
Mexico	255,862	27.1	1.1	2.7	ms
New Zealand	17,299	3.8	2.2	5.6	ms - MS
PNG	7,123	0.6	0.8	2.0	NS
Peru	57,029	26.0	4.6	11.7	S
Philippines	6,357	0.7	1.1	2.8	ms
Russia	369,176	60.7	1.6	4.2	ms
Chinese Taipei	693	0.2	3.2	8.1	MS
Thailand	17,253	4.1	2.4	6.1	ms - MS
United States	1,214,007	148.3	1.2	3.1	ms
Viet Nam	21,090	4.4	2.1	5.4	ms
Total	4,033,039	538.8	1.3	3.4	ms

Note: Biofuels refer to ethanol fuel; columns two and three are derived from Table 4 to obtain biofuels density; * 0.39 m^3 per tonne biomass; NS – not suitable; ms – marginally suitable; MS – moderately suitable; S – suitable.

Of the nineteen economies analyzed here, only four (New Zealand; Peru; Chinese Taipei; and Thailand) have Suitable or Moderately Suitable yields on average. These economies generally have better soils, warm tropical climate, and adequate rainfall on their marginal lands. Twelve economies are on average marginally suitable and three are unsuitable for biofuels feedstock production, though this overview could conceal some portions of these economies with a higher potential.

The preponderance of the large area economies (six economies with more than 250,000 km^2 of marginal lands) in the lowest classes of suitability demonstrates that while they account for 80% of the estimated total ethanol potential on such lands, the economic costs will be high. Note also that this study did not attempt to estimate the existing above ground biomass or the carbon currently in the soil. As a result, it is not certain that such low productivity lands would necessarily pay back their carbon debt if converted to biomass for biofuel production. This situation was evaluated using the GorCam model for forest lands and clearly demonstrated that there is a productivity threshold to having a positive carbon balance over a reasonable number of years (Schlamadinger and Marland 1996).

Our conclusions are somewhat similar to those of Campbell J.E., et al. (2008), who found that the highest classifications are with tropical abandoned grass lands ranging from Moderately Suitable to Very Suitable. But these are hot spots and the global weighted area average of all of the abandoned agricultural lands was found to be marginally suitable for above ground biomass.

Conclusions

Marginal lands present severe constraints to plant mass production. Non-optimum conditions of pH, poor soils, inadequate or excessive water availability, and steep terrain all present major challenges to sustainable biomass production without major investments.

Amelioration of these lands is possible through investment in irrigation and conservation schemes, but is often very expensive. Examples abound of irrigation projects in areas of dryness such as the Red Flag (Hongi) canal in the Taihang Mountains of China or the extensive schemes of the Murray-Darling Basin of Australia. Similarly, the management of both slope and water in the ancient rice terraces of the Ifuago in the cordillera of northern Luzon in the Philippines is an example of overcoming limitations in a sustainable way. Many of the other APEC economies have examples of such amelioration.

The goal of this study was to examine the marginal lands in APEC economies and evaluate their biomass productivity potential. The marginal lands were identified using the GAEZ system of the FAO. The study's biomass production assessment methodology was to take the defined areas and to look at their status today. It used a combination of assessment of the current vegetation cover and a calculation of the net primary productivity. This is an assessment of the potential of a given land parcel on an "as-is" basis, without any attempt to estimate the potential under conditions that would prevail if improvements such as irrigation were undertaken. A note of caution is that it is based on a snapshot of a particular year: the northern hemisphere growing season of 2000 and the southern hemisphere season of 2000 -2001. This growth year window was a La Nina period of the El Nino Southern Oscillation (ENSO) in the Pacific region, a period of relatively high rainfall in Australia prior to the extended drought that started in 2002-3 and has continued to the present. On the other hand, the assumptions about the rate at which plants convert sunlight to biomass are quite conservative in view of agricultural advancements.

Many of the marginal lands in APEC economies are in regions that are relatively dry, as illustrated at a glance in Figure 2. These include regions with rain deficit adjacent to the major mountain chains of North and South America, Asia and Australia. Data for the tropical regions such as the Asian Islands are unlikely to be as affected as much by the time window chosen, though even so the ENSO still has some effects.

The net primary productivity, in tonnes of carbon, was derived from extensive data sets and translated into annual yield of lignocellulosic biomass, typical of grasses such as switchgrass and other thin-stemmed perennials, or thick-stemmed grasses in tropical areas. Other lignocellulosics that would be similar are short-rotation tree species with willow and poplar as examples in temperate regions and eucalyptus in more tropical environments. These crop types meet the criteria of non-edible crops and will give the highest biomass potential.

The biomass yield was translated into suitability bands, calculated for each economy on average and not for each 100 km^2 cell separately. Very Suitable (VS) and Suitable (S) lands with yields greater than 10 t/ha/yr can be considered economically viable as the areas needed are compact and the harvesting effort is minimized. Moderately suitable (MS) lands of 7-10 t/ha/yr may also have significant economic potential. As biomass productivity declines, the areas for a given output increase; harvesting effort not only increases, but the efficiency goes down, more equipment is needed and the logistics of biomass delivery to the biofuel processing plants become more challenging. The marginal suitable (ms) category is a yield of 3 - 5 t/ha/yr and the unsuitable areas (NS) have a productivity of less than 2 t/ha/yr. The ms and NS categories do not preclude the development and use of biomass for local markets, but would not offer an economic proposition in terms of large scale biofuel production for domestic or export markets.

Among the APEC economies, only Thailand's marginal lands achieved an average score of Suitable, while the marginal lands of three economies (Brunei; China; and Papua New Guinea) were rated as unsuitable for biofuels feedstock production. The marginal lands in the remaining economies were in the range of marginally to moderately suitable, and represent 90% of the initial land area assessed. Again, it should be noted that this analysis is done for each economy on average, ignoring potential hot spots.

The total annual biomass resource potential on marginal lands in APEC economies appears to be around 1.3 Gt, which translates roughly into about 540 hm^3 of ethanol fuel (260 Mt of gasoline equivalent). Current gasoline consumption in the APEC region is about 621 Mt and crude oil import is approximately 1.3 Gt (IEA 2006). Therefore the ethanol volume from marginal lands would displace two-fifths of the region's gasoline consumption and one-fifth of its crude oil import.

Many economies could replace a substantial volume of their current gasoline consumption and crude oil import with ethanol from marginal lands, as illustrated in the Appendix. These include Peru; Australia; Chile; Viet Nam; and New Zealand. But there could be technical or economic restrictions on the use of these lands, which suggests that only a portion of this potential can be realized. This portion would be different in each economy and could be determined by a detailed techno-economic feasibility assessment, which is beyond the scope of this study.

Previous work by the authors (Milbrandt, A., Overend, R. 2008) evaluated the ethanol potential from existing lignocellulosic biomass (primarily crop and forest residues) in the APEC region. The study estimated similar volume of ethanol potential, 509 hm^3 of ethanol fuel or 245 Mt of gasoline equivalent, enough to displace two-fifths of the region's gasoline consumption and one-fifth of its crude oil import. Comparing the results from both studies at an economy level, it appears that in some economies (such as China; Indonesia; Japan; Korea; Malaysia; the Philippines; Thailand; and Viet Nam) it might be best to utilize the existing lignocellulosic biomass rather than to develop their marginal lands. The ethanol potential from these resources is much higher than that from marginal lands (Table 7 and Table 8 in the Appendix). On the other hand, economies such as Australia; Canada; Chile; Mexico; New Zealand; Russia; and the United States should consider developing their marginal lands given their high biomass, and ethanol production potential. However, large lignocellulosic biomass resources exist in those economies as well. Therefore, a combination of feedstock — lignocellulosic biomass from farm and forest residues and purposely grown on marginal lands — would assure a sustainable biomass resource supply for biofuels production in these economies. Such production could substantially displace current petroleum products' import and consumption.

The present study evaluates only the ethanol potential on marginal lands. Biodiesel could present very good opportunities for some of these lands in tropical regions, so future work should evaluate the biodiesel potential on marginal lands in APEC economies and compare it with the results from the previous study. More detailed assessments at a sub-regional or an economy level, with particular attention to multi-year series of NPP data and a finer than 100 km^2 spatial resolution, would also provide a better understanding of the biofuels potential on marginal lands in the APEC region. Since interest in biofuels is in large part driven by greenhouse gas mitigation policies, future resource assessment work could be linked to climate modeling efforts, which are now starting to have the ability to predict regional changes in climate that would affect biofuel output.

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APPENDIX

Table 6 Ethanol Potential from Marginal Lands, Share of Current Gasoline Consumption and Crude Oil Import in APEC Economies

Economy	Biomass Resource Potential ('000 tonnes)	Ethanol Potential (hm3)	Gasoline Equivalent ('000 tonnes)	Gasoline Consumption ('000 tonnes)*	Share of Gasoline Consumption (%)	Crude Oil Import ('000 tonnes)*	Share of Crude Oil Import (%)
Australia	389,564	153.1	73,754	13,743	536.7	18,837	391.5
Brunei	11	0.004	1.9	202	1.0		
Canada	98,521	38.7	18,643	30,085	62.0	41,468	45.0
Chile	39,120	15.4	7,419	2,079	356.8	10,664	69.6
China	122,719	48.2	23,220	49,870	46.6	145,175	16.0
Indonesia	15,494	6.1	2,939	13,055	22.5	15,344	19.2
Japan	1,924	0.8	385	44,083	0.9	197,500	0.2
Korea	588	0.2	96	7,013	1.4	119,440	0.1
Malaysia	1,052	0.4	193	7,888	2.4	7,861	2.5
Mexico	69,000	27.1	13,055	29,712	43.9		
New Zealand	9,599	3.8	1,831	2,347	78.0	4,591	39.9
PNG	1,432	0.6	289	N/A	N/A	435	66.4
Peru	66,225	26	12,525	752	1,665.6	5,078	246.7
The Philippines	1,793	0.7	337	2,619	12.9	10,735	3.1
Russia	154,412	60.7	29,241	27,893	104.8		
Chinese Taipei	558	0.2	96	7,649	1.3	51,682	0.2
Thailand	10,394	4.1	1,975	5,263	37.5	39,892	5.0
United States	377,413	148.3	71,441	372,851	19.2	537,755	13.3
Viet Nam	11,281	4.4	2,120	2,690	78.8		
APEC Total	**1,371,098**	**538.8**	**259,561**	**619,794**	**41.9**	**1,206,457**	**21.5**

* Source: IEA 2006; gray areas – not applicable; N/A – information not available

Table 7 Ethanol Potential from Existing Biomass Resources, Share of Current Gasoline Consumption and Crude Oil Import in APEC Economies

Economy	Feedstock Type	Resource Availability ('000 tonnes)	Ethanol Potential (hm3)	Gasoline Equivalent ('000 tonnes)	Gasoline Consumption ('000 tonnes)*	Share of Gasoline Consumption (%)	Crude Oil Import ('000 tonnes)*	Share of Crude Oil Import (%)
Australia	crop, forest, and primary mill residues; urban wood waste	36,700	11.0	5,299	14,520	36.5	20,070	26.4
Brunei					196			
Canada	crop, forest, and primary mill residues; hog fuel piles	71,000	21.3	10,261	29,751	34.5	45,336	22.6
Chile	primary mill residues	3,254	0.9	434	2,081	20.8	10,219	4.2
China	crop, forest, and primary mill residues	788,000	236.0	113,689	46,097	246.6	126,817	89.6
Hong Kong					325		352	
Indonesia	crop residues; sugar cane bagasse; oil-palm, rubber, and coconut residues	74,000	22.2	10,695	12,942	82.6	20,829	51.3
Japan	crop and forest residues; urban wood waste	15,000	4.5	2,168	44,391	4.9	207,266	1.0
Korea	crop and forest residues	13,100	3.9	1,879	6,969	27.0	113,234	1.7
Malaysia	crop residues; sugar cane bagasse; oil-palm and wood-processing residues	32,392	9.7	4,673	7,756	60.2	7,885	59.3
Mexico	crop, logging, and primary mill residues	74,500	22.4	10,767	27,704	38.9		
New Zealand	crop, logging, and primary mill residues; horticultural and urban wood waste	5,500	1.7	795	2,325	34.2	4,488	17.7
PNG	logging, oil-palm, and coconut residues; sugar cane bagasse	N/A	N/A	N/A	N/A	N/A	435	N/A
Peru	crop, logging, and oil-palm residues; sugar cane bagasse	N/A	N/A	N/A	771	N/A	4,809	N/A
The Philippines	crop, logging, and coconut residues; sugar cane bagasse	18,000	5.4	2,601	4,111	63.3	10,681	24.4
Russia	crop and forest residues	100,000	30.0	14,452	26,260	55.0		
Singapore					727		54,786	
Chinese Taipei	crop residues	1,900	0.6	275	7,845	3.5	54,035	0.5
Thailand	crop residues; sugar cane bagasse; oil-palm and coconut residues	47,800	14.3	6,889	5,280	130.5	39,815	17.3
United States	crop, forest, primary mill, and secondary mill residues; urban wood waste	324,448	97.3	46,873	373,930	12.5	538,651	8.7
Viet Nam	crop, wood-processing, and coconut residues; sugar cane bagasse	93,000	27.9	13,440	2,546	527.9		
APEC Total		**1,698,594**	**509.0**	**245,189**	**616,527**	**39.8**	**1,259,708**	**19.5**

Source: Milbrandt, A., Overend, R. 2008; * IEA, 2005; gray areas – not applicable; N/A – information not available

Australia

Total land area – 7,694,273 km^2

Population - 20,434,176

Marginal lands - 1,036,239 km^2 (13.5% of total area)

Biomass resource potential on marginal lands – 389,564,000 tonnes/year

Ethanol potential from marginal lands – 153 hm^3 (537% of current gasoline consumption)

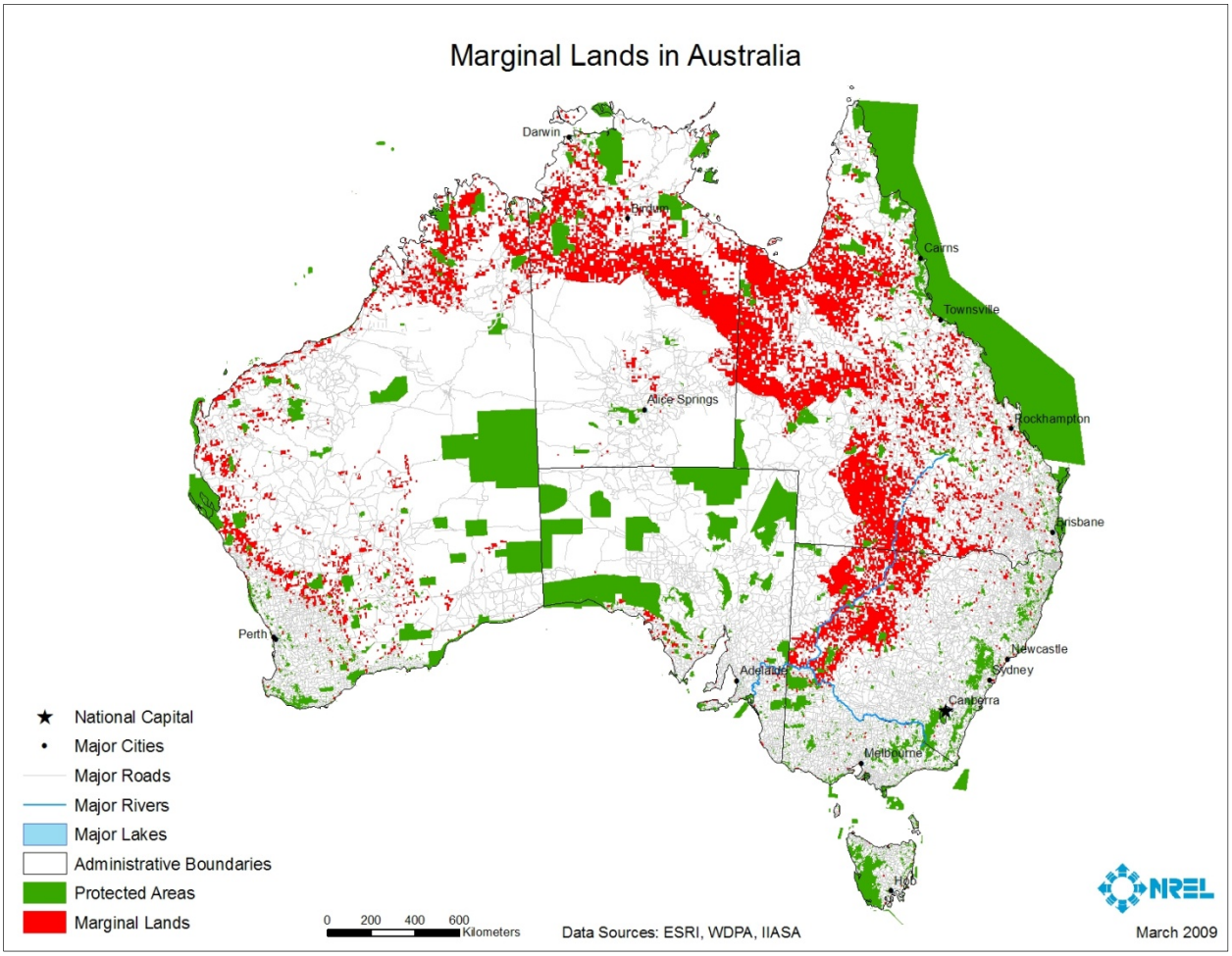

Figure 5 Marginal Lands in Australia

Brunei Darussalam

Total land area – 6,078 km^2

Population – 386,511

Marginal lands - 85 km^2 (1.4% of total area)

Biomass resource potential on marginal lands – 10,723 tonnes/year

Ethanol potential from marginal lands – 0.004 hm^3 (1% of current gasoline consumption)

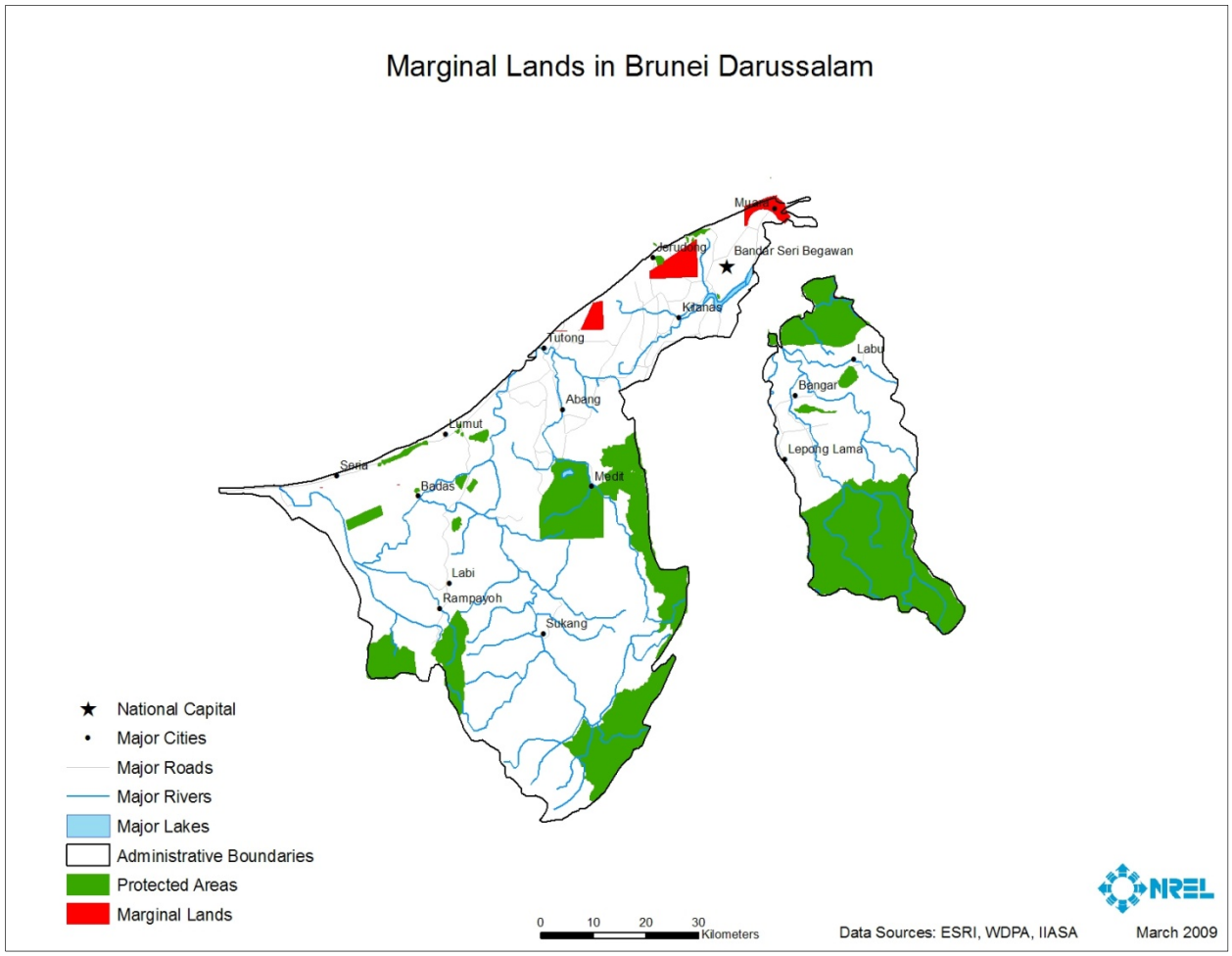

Figure 6 Marginal Lands in Brunei Darussalam

Canada

Total land area – 9,832,884 km^2

Population - 33,390,141

Marginal lands - 376,092 km^2 (3.8% of total area)

Biomass resource potential on marginal lands – 98,521,000 tonnes/year

Ethanol potential from marginal lands – 38.7 hm^3 (62% of current gasoline consumption)

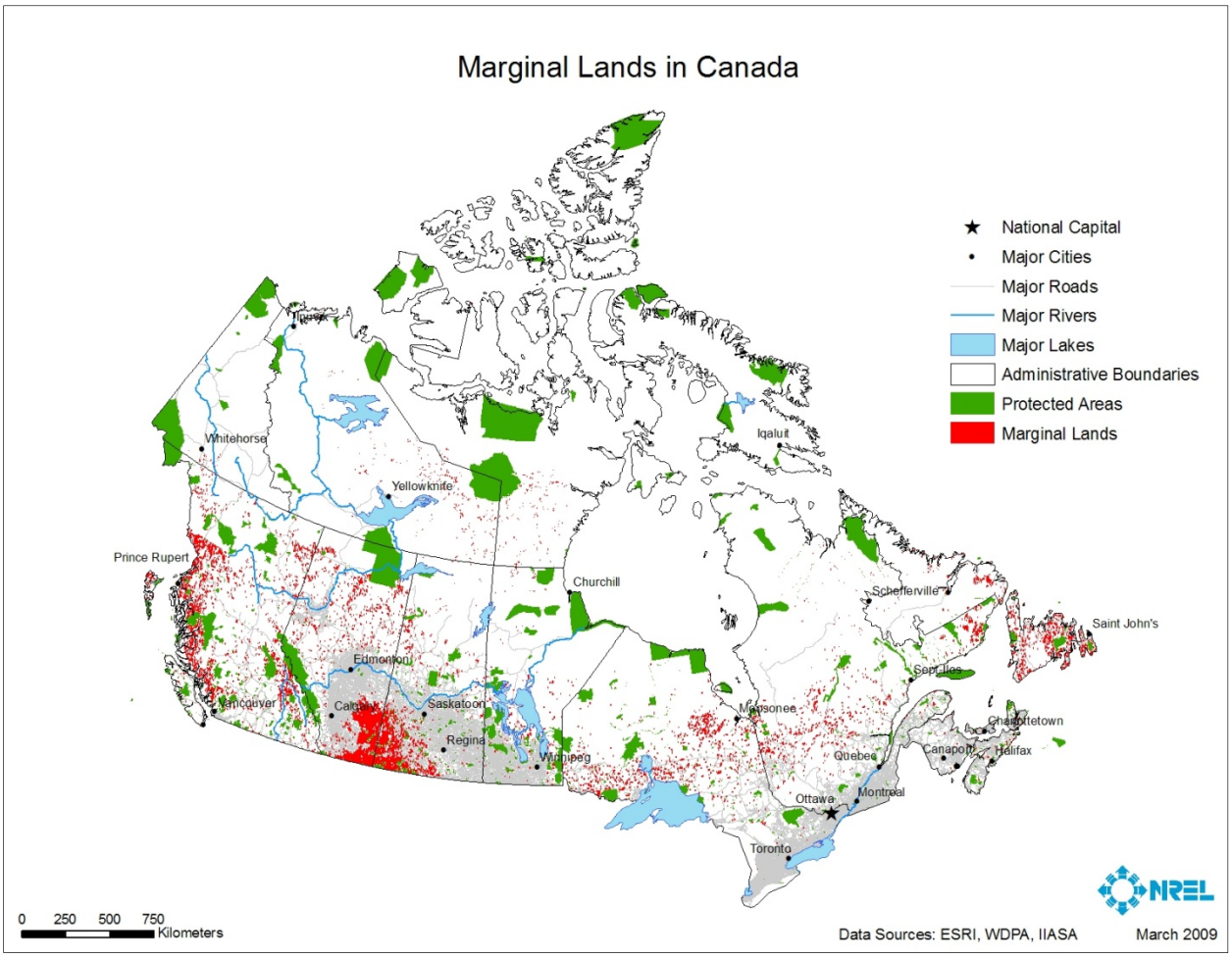

Figure 7 Marginal Lands in Canada

Chile

Total land area – 722,511 km^2

Population - 16,284,741

Marginal lands - 95,645 km^2 (13% of total area)

Biomass resource potential on marginal lands – 39,120,000 tonnes/year

Ethanol potential from marginal lands – 15.4 hm^3 (357% of current gasoline consumption)

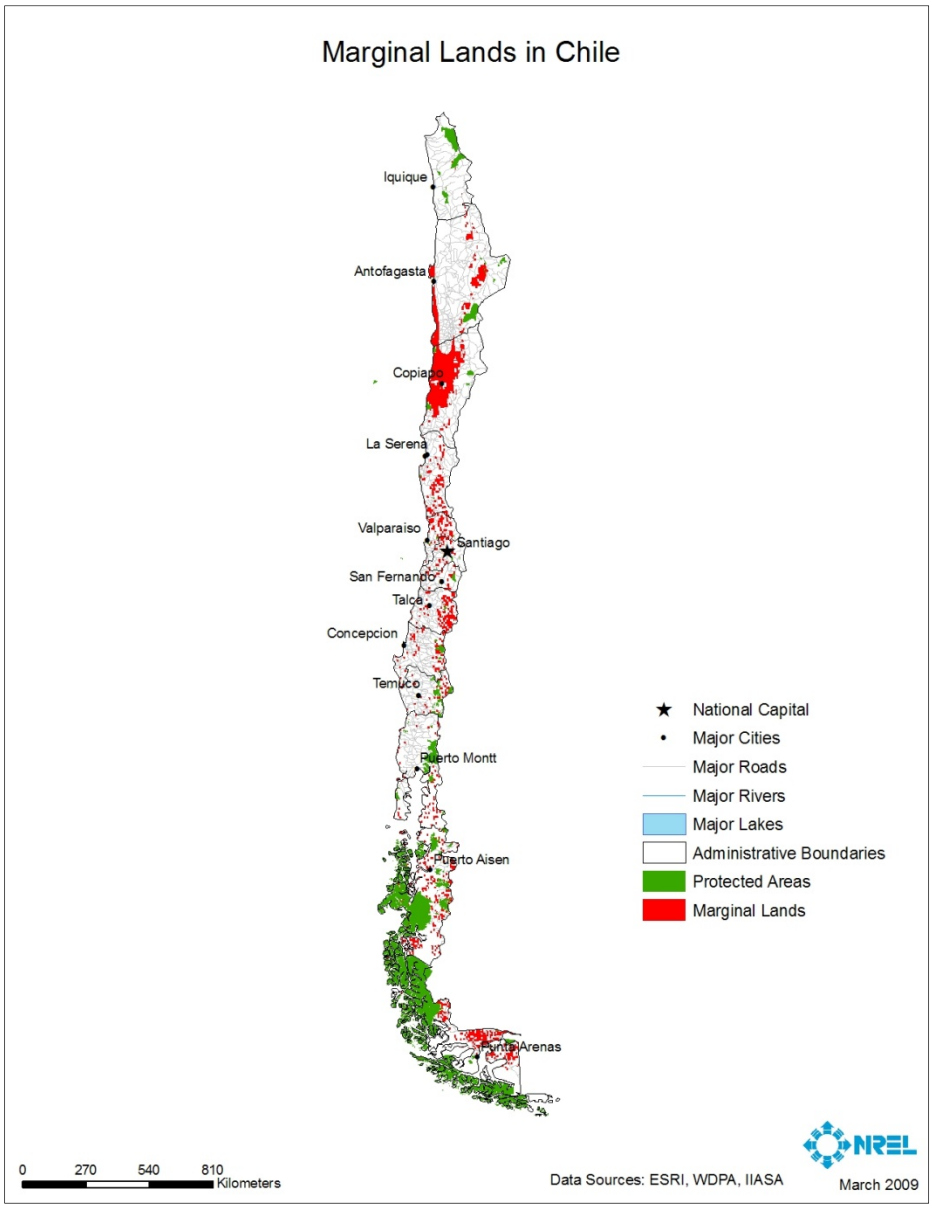

Figure 8 Marginal Lands in Chile

China

Total land area – 9,402,887 km^2

Population - 1,321,851,888

Marginal lands - 511,905 km^2 (5.4% of total area)

Biomass resource potential on marginal lands – 122,719,000 tonnes/year

Ethanol potential from marginal lands – 48 hm^3 (47% of current gasoline consumption)

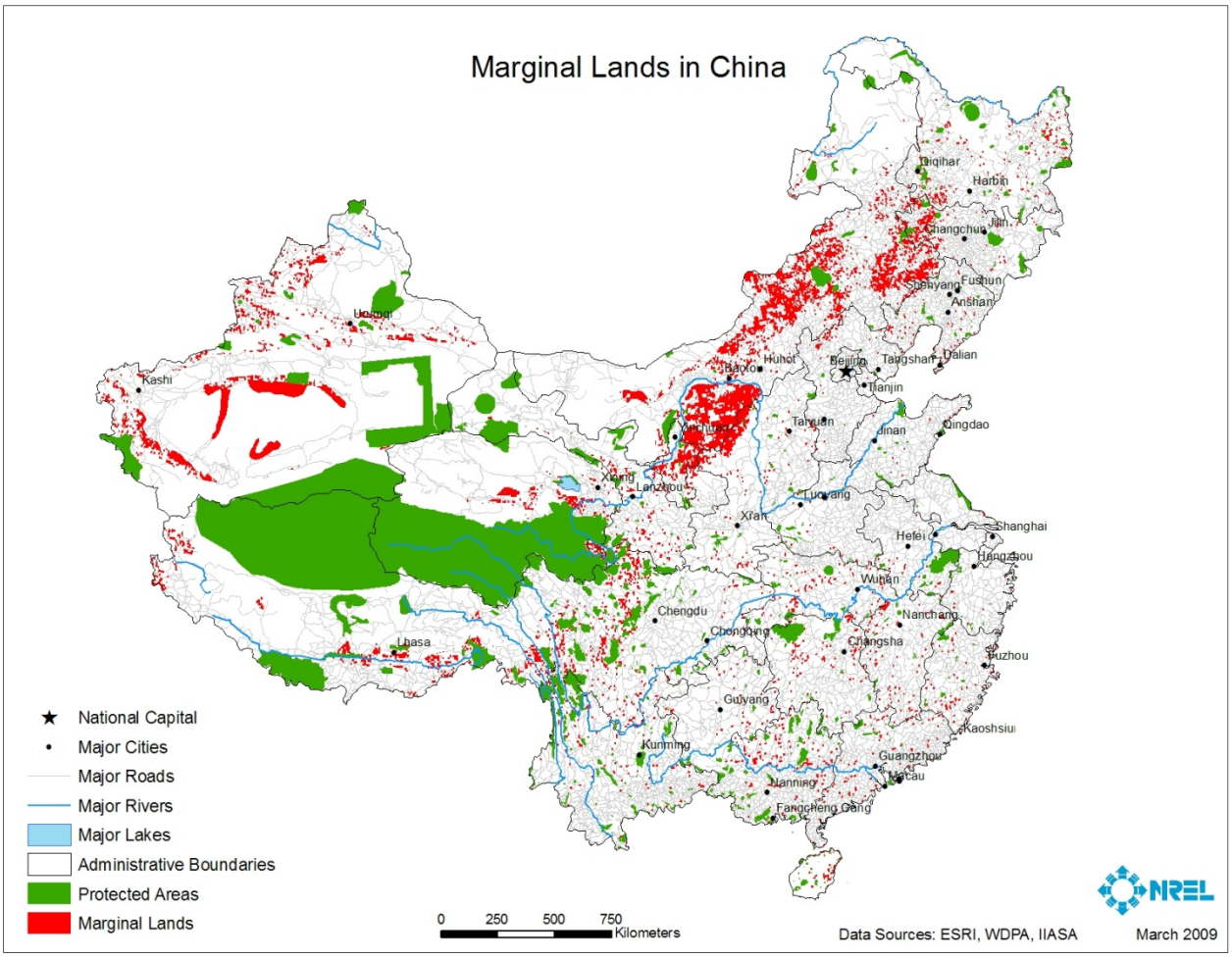

Figure 9 Marginal Lands in China

Indonesia

Total land area – 1,847,033 km^2

Population - 234,693,997

Marginal lands - 37,123 km^2 (2% of total area)

Biomass resource potential on marginal lands – 15,494,000 tonnes/year

Ethanol potential from marginal lands - 6 hm^3 (23% of current gasoline consumption)

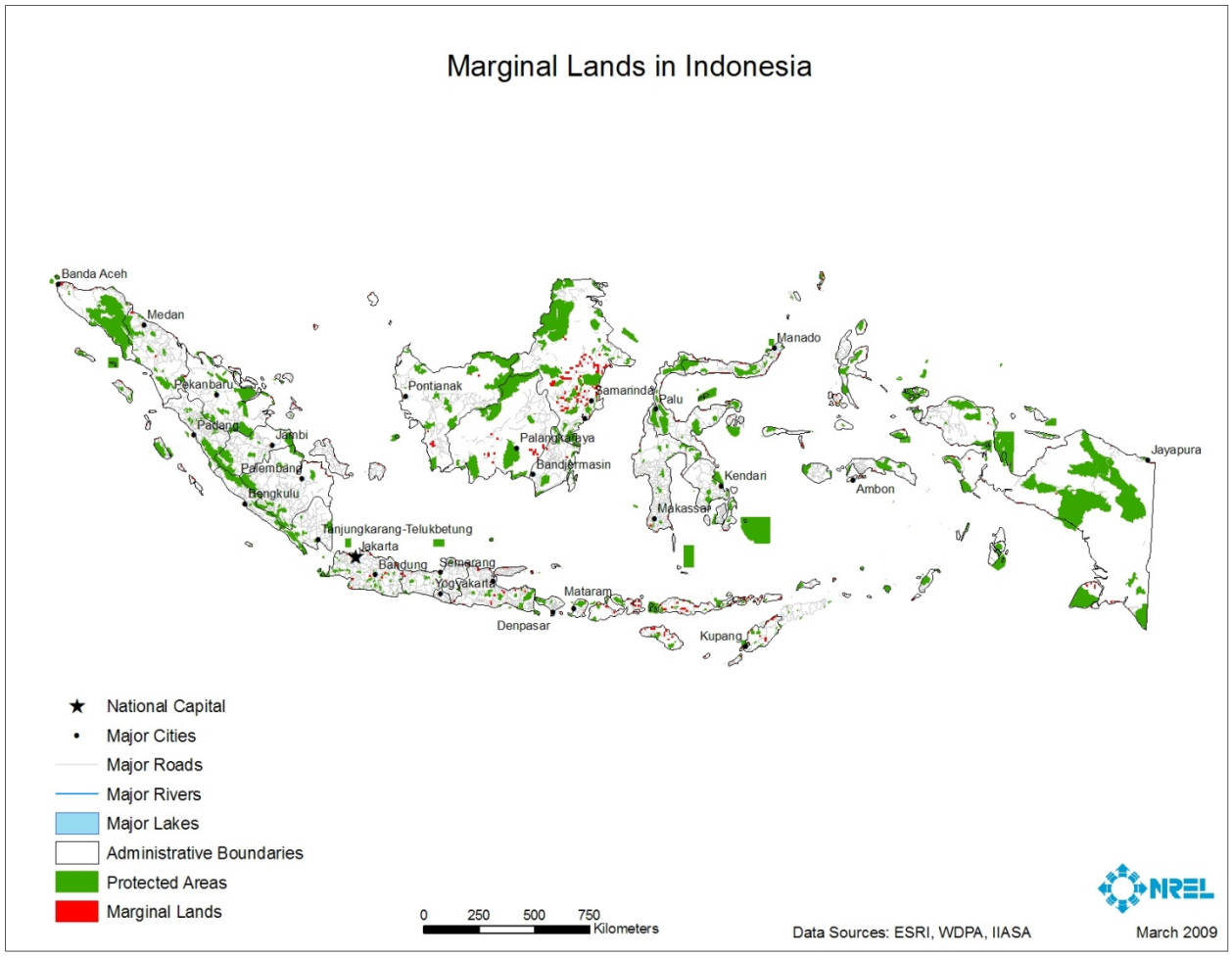

Figure 10 Marginal Lands in Indonesia

Japan

Total land area – 370,727 km^2

Population - 127,467,972

Marginal lands - 4,878 km^2 (1.3% of total area)

Biomass resource potential on marginal lands – 1,924,000 tonnes/year

Ethanol potential from marginal lands – 0.8 hm^3 (1% of current gasoline consumption)

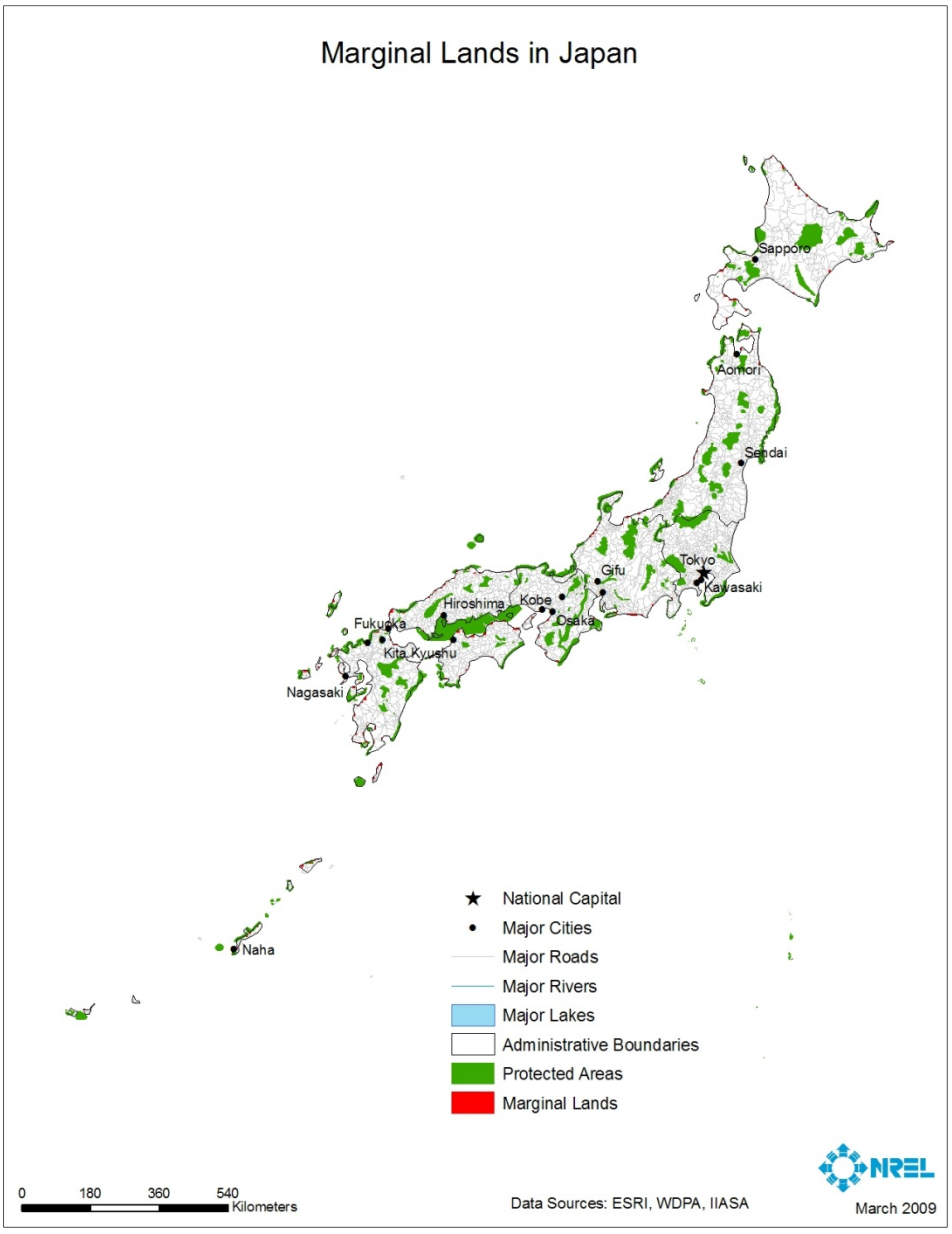

Figure 11 Marginal Lands in Japan

Republic of Korea

Total land area – 94,773 km^2

Population - 49,044,790

Marginal lands - 1,651 km^2 (1.7% of total area)

Biomass resource potential on marginal lands – 588,000 tonnes/year

Ethanol potential from marginal lands – 0.2 hm^3 (1.4% of current gasoline consumption)

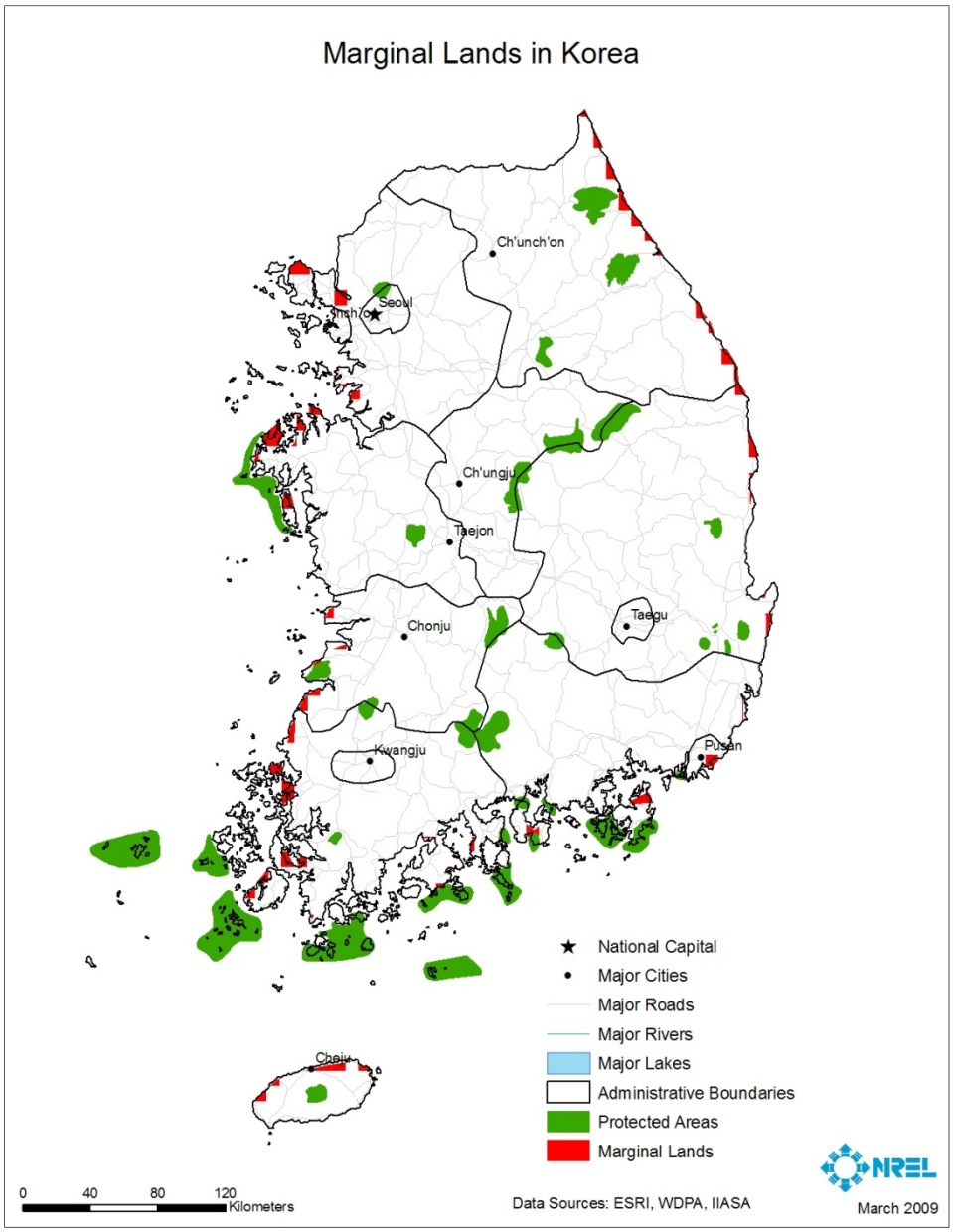

Figure 12 Marginal Lands in Republic of Korea

Malaysia

Total land area – 328,536 km^2

Population - 24,821,286

Marginal lands - 3,534 km^2 (1% of total area)

Biomass resource potential on marginal lands – 1,000,000 tonnes/year

Ethanol potential from marginal lands – 0.4 hm^3 (2.4% of current gasoline consumption)

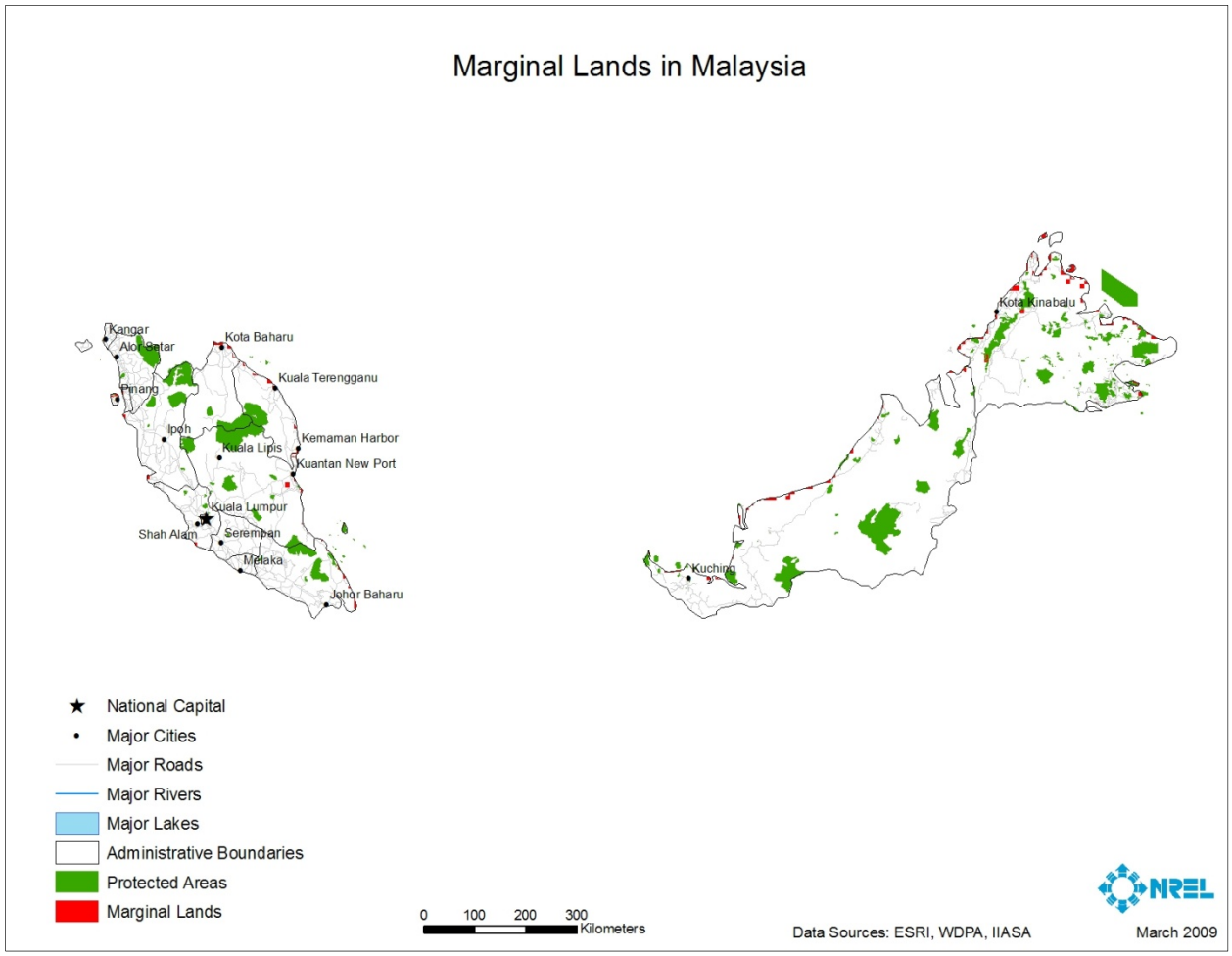

Figure 13 Marginal Lands in Malaysia

Mexico

Total land area – 1,953,851 km^2

Population - 108,700,891

Marginal lands - 255,862 km^2 (13% of total area)

Biomass resource potential on marginal lands – 69,000,000 tonnes/year

Ethanol potential from marginal lands – 27 hm^3 (44% of current gasoline consumption)

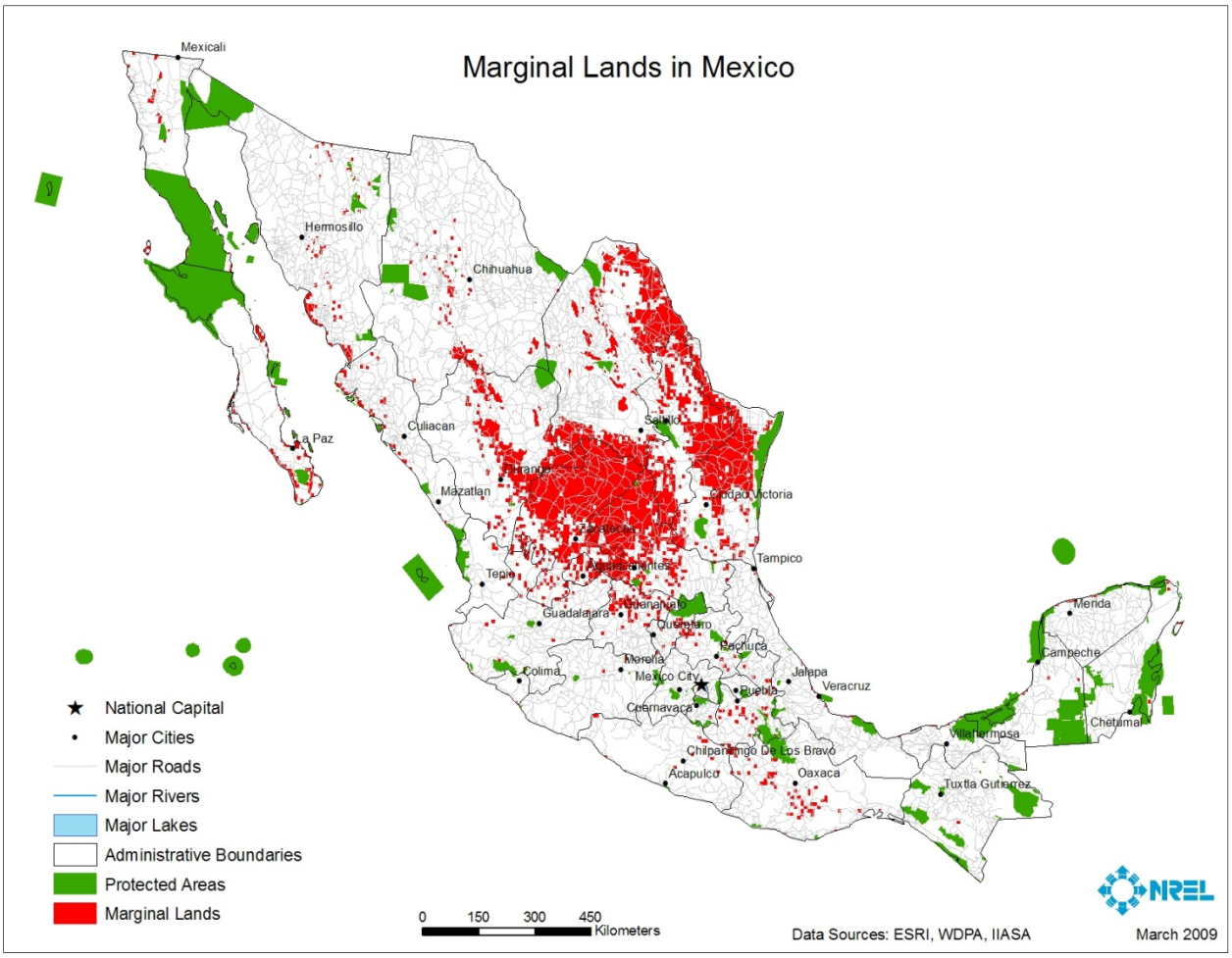

Figure 14 Marginal Lands in Mexico

New Zealand

Total land area – 267,214 km^2

Population - 4,115,771

Marginal lands - 17,299 km^2 (6.5% of total area)

Biomass resource potential on marginal lands – 9,599,000 tonnes/year

Ethanol potential from marginal lands – 3.8 hm^3 (78% of current gasoline consumption)

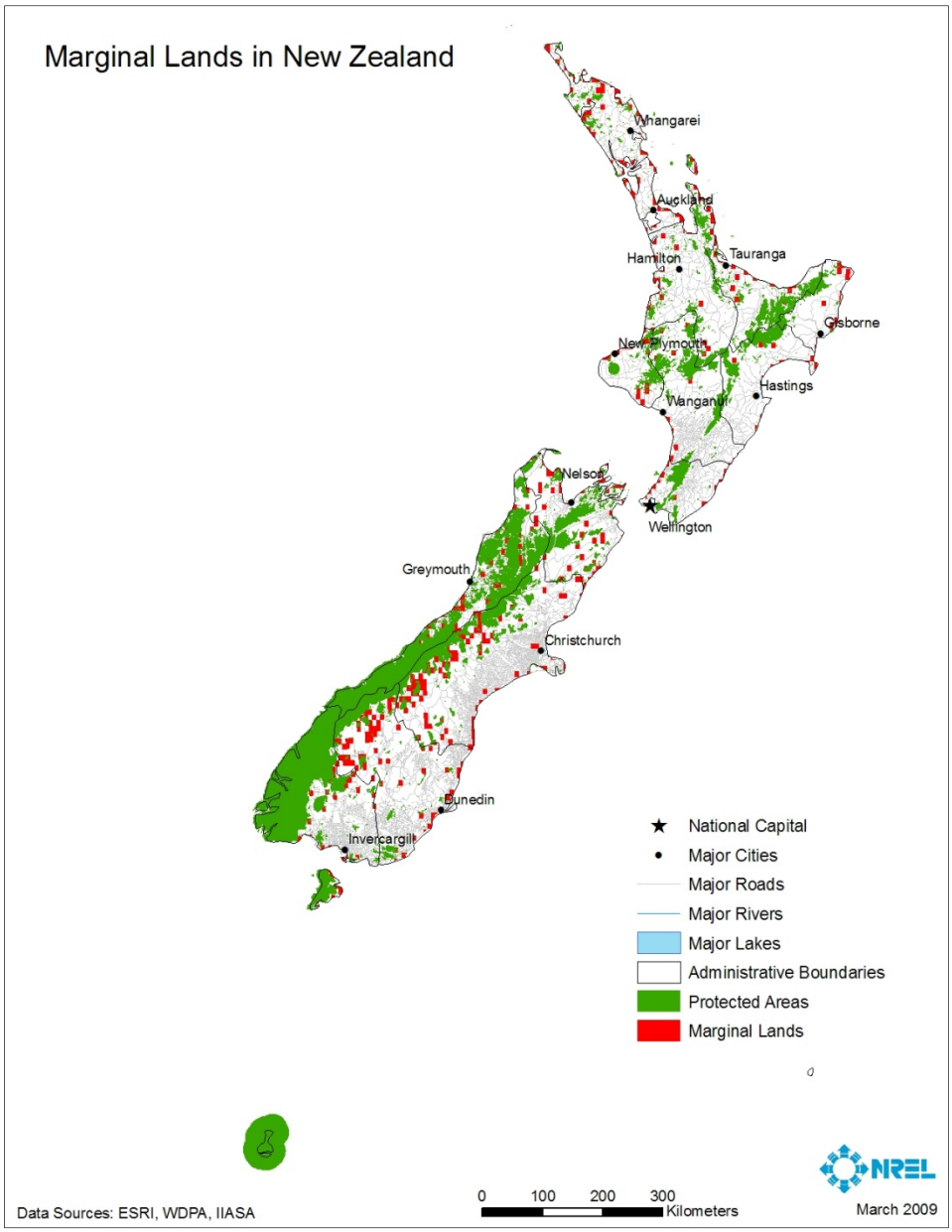

Figure 15 Marginal Lands in New Zealand

Papua New Guinea

Total land area – 458,666 km^2

Population - 5,795,887

Marginal lands – 7,123 km^2 (1.6% of total area)

Biomass resource potential on marginal lands – 1,432,000 tonnes/year

Ethanol potential from marginal lands – 0.6 hm^3 (current gasoline consumption not available)

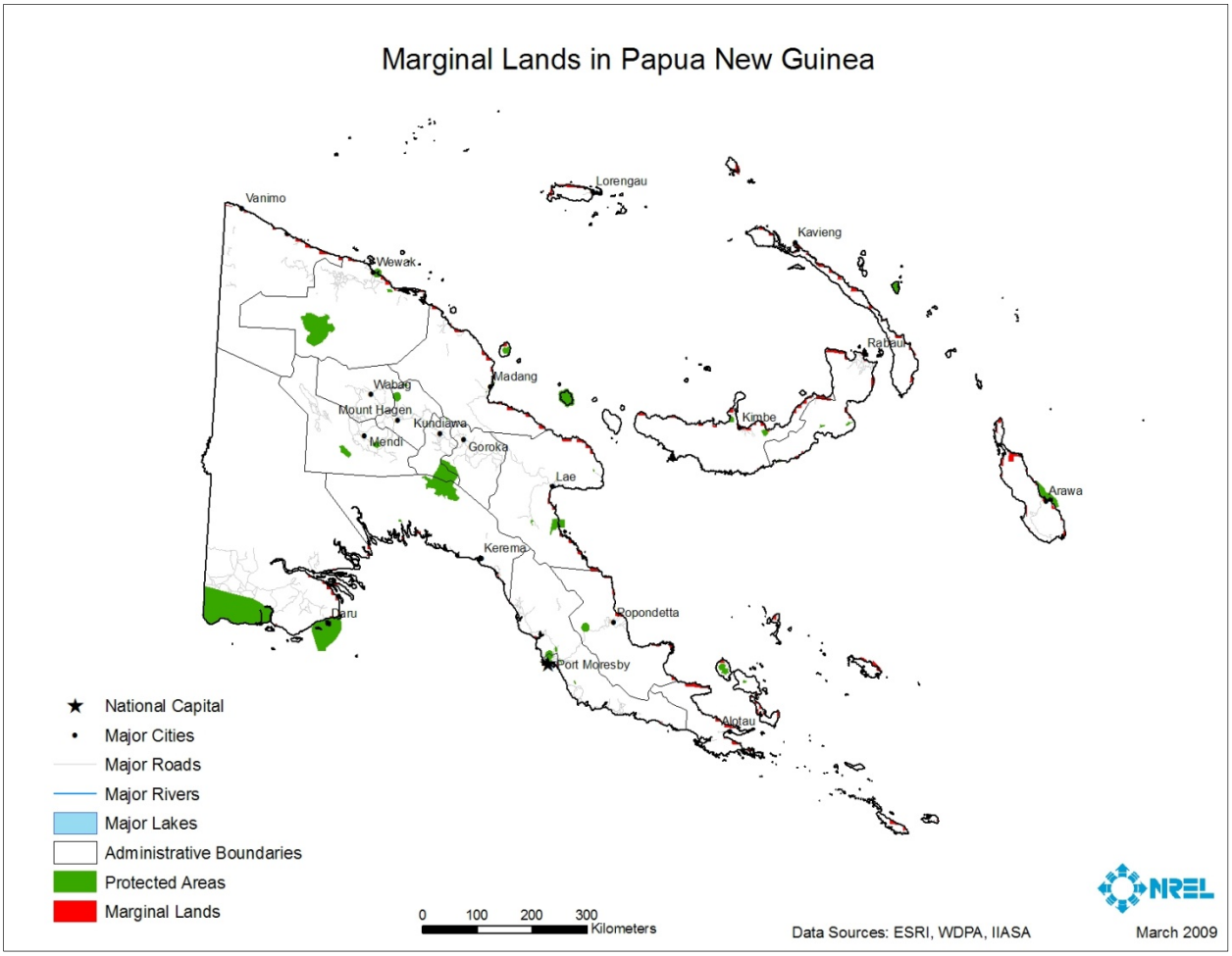

Figure 16 Marginal Lands in Papua New Guinea

Peru

Total land area – 1,296,605 km^2

Population - 28,674,757

Marginal lands - 57,029 km^2 (4.4% of total area)

Biomass resource potential on marginal lands – 66,225,000 tonnes/year

Ethanol potential from marginal lands – 26 hm^3 (1,666% of current gasoline consumption)

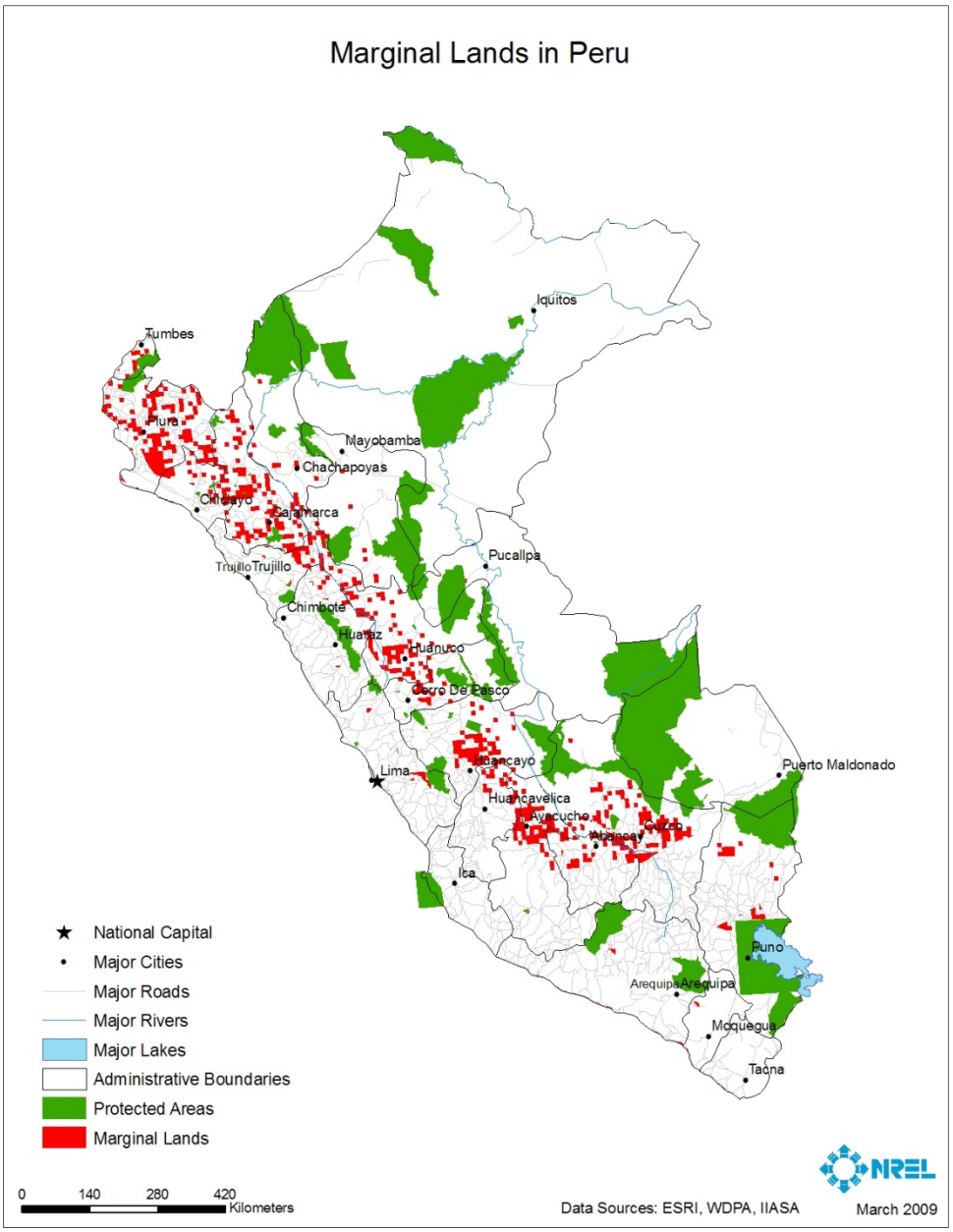

Figure 17 Marginal Lands in Peru

Philippines

Total land area – 280,958 km^2

Population - 91,077,287

Marginal lands – 6,357 km^2 (2.3% of total area)

Biomass resource potential on marginal lands - 1,793,000 tonnes/year

Ethanol potential from marginal lands – 0.7 hm^3 (13% of current gasoline consumption)

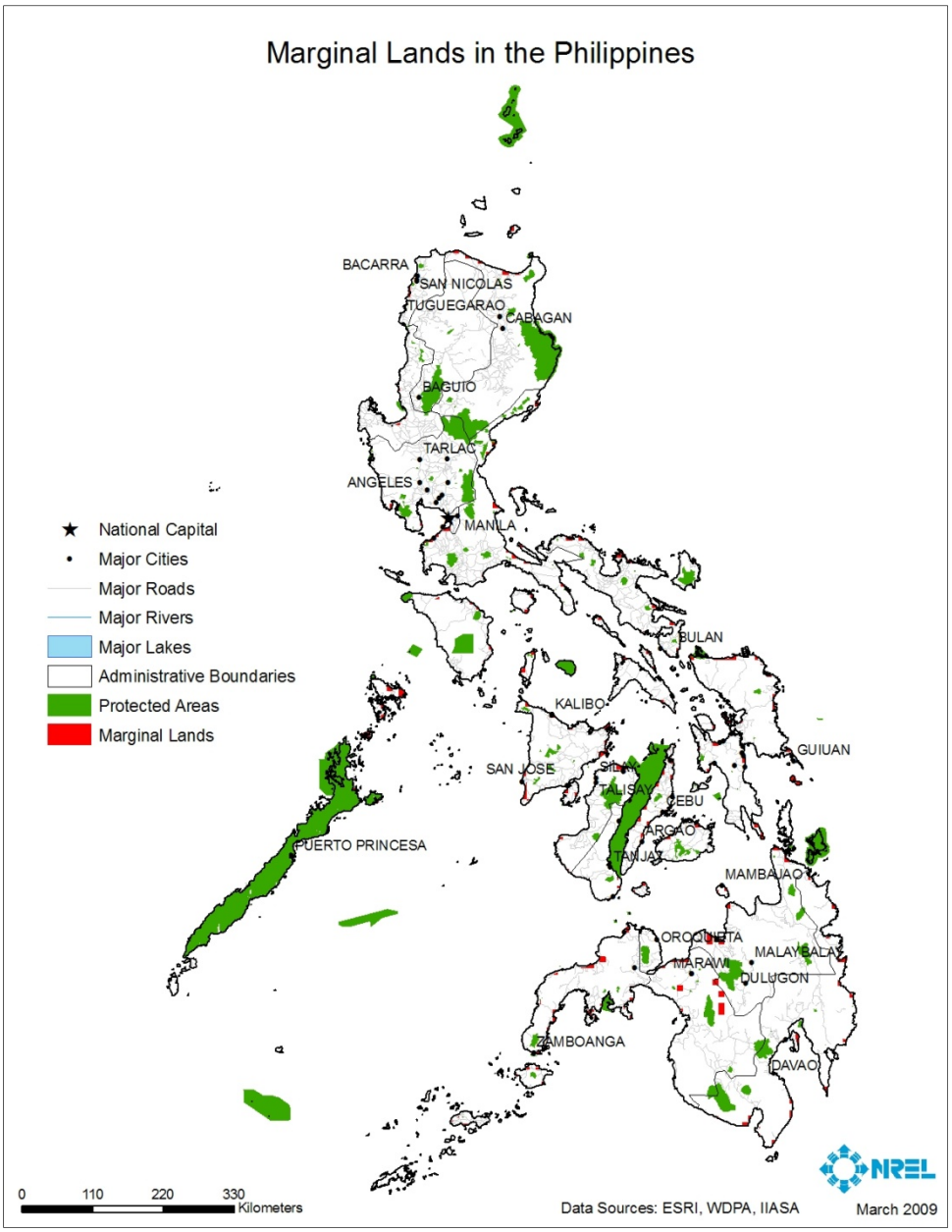

Figure 18 Marginal Lands in the Philippines

Russia

Total land area – 16,897,294 km^2

Population - 141,377,752

Marginal lands - 369,176 km^2 (2.2% of total area)

Biomass resource potential on marginal lands – 154,412,000 tonnes/year

Ethanol potential from marginal lands – 61 hm^3 (105% of current gasoline consumption)

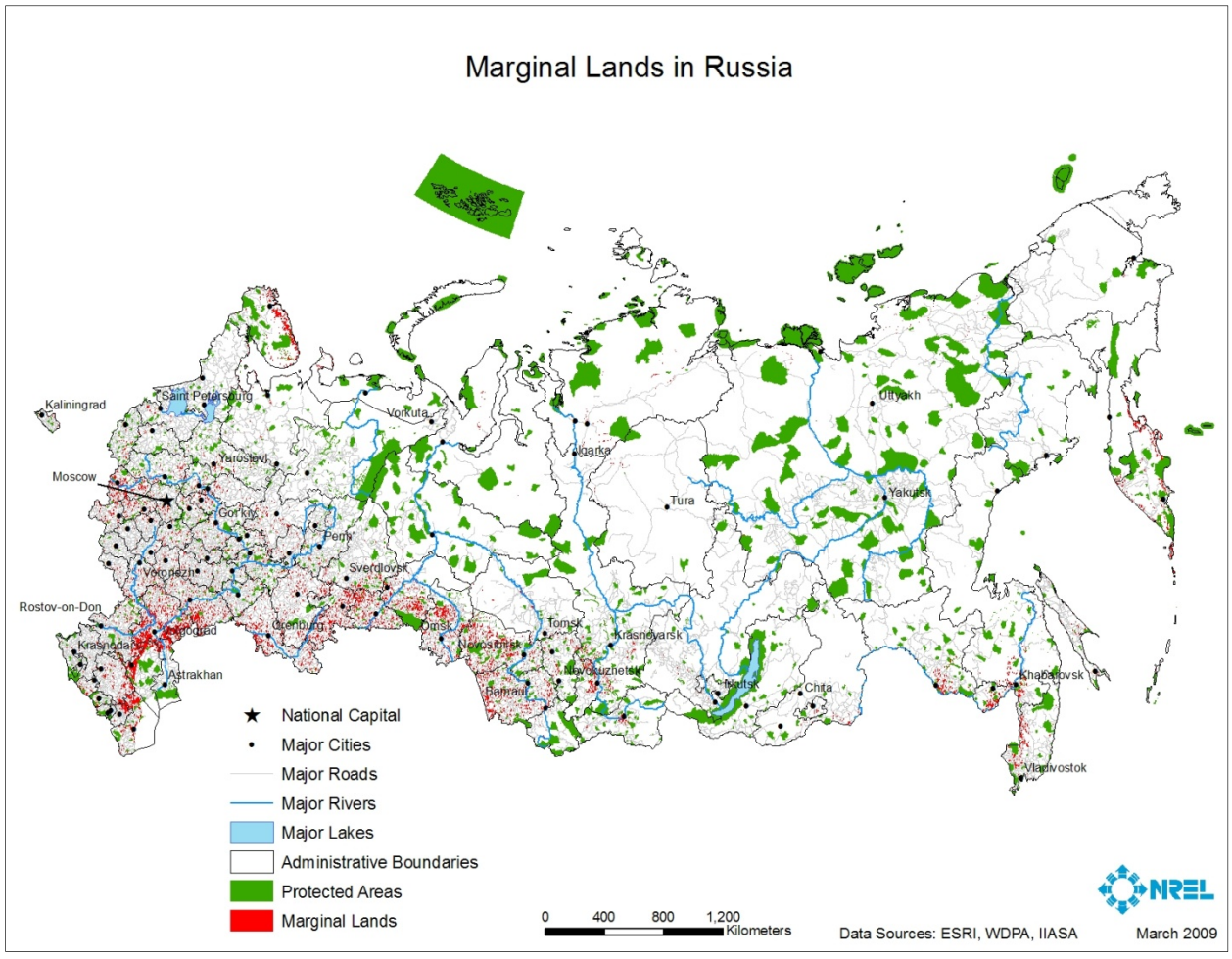

Figure 19 Marginal Lands in Russia

Chinese Taipei

Total land area – 35,980 km^2

Population - 22,858,872

Marginal lands - 693 km^2 (2% of total area)

Biomass resource potential on marginal lands – 558,000 tonnes/year

Ethanol potential from marginal lands – 0.2 hm^3 (1.3% of current gasoline consumption)

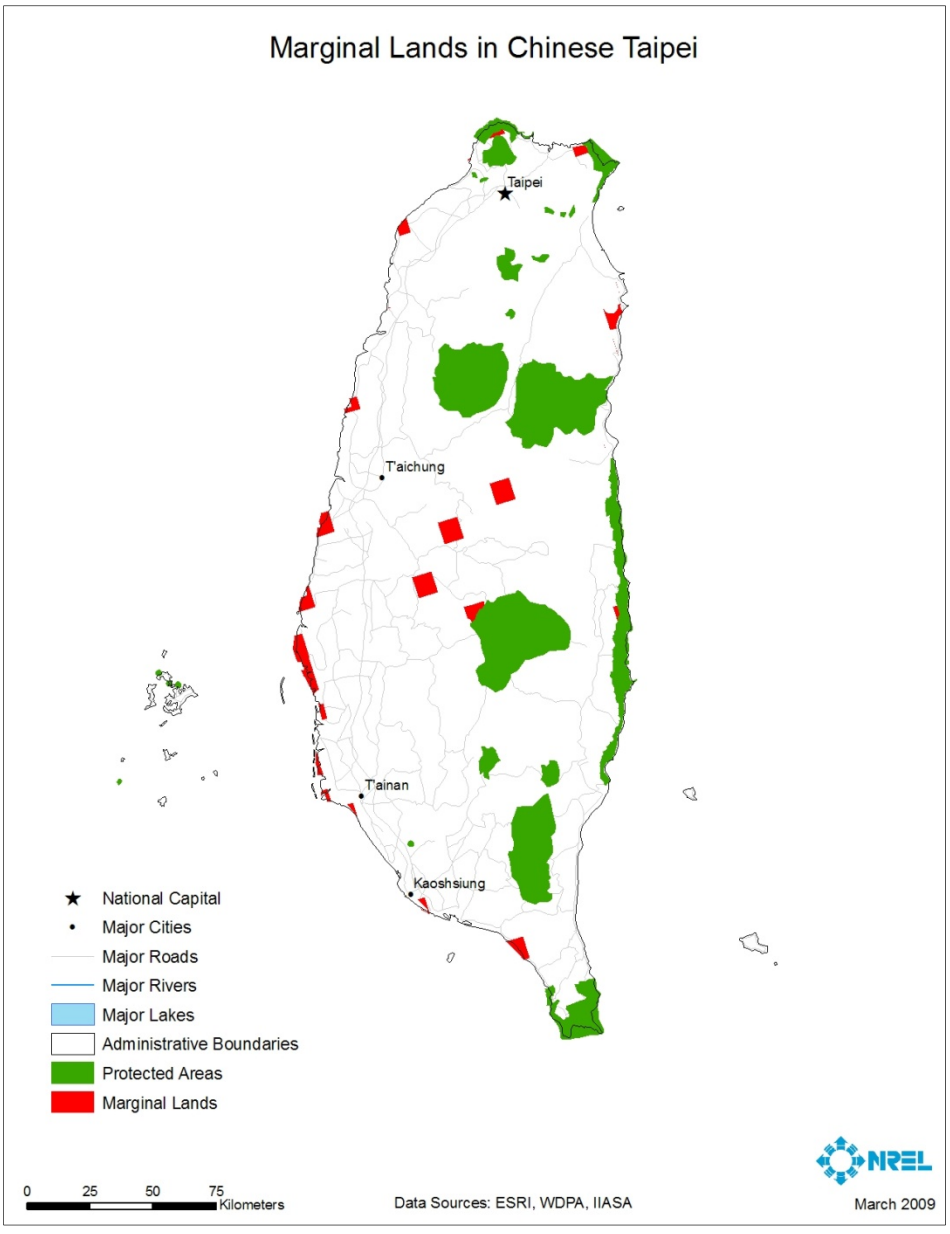

Figure 20 Marginal Lands in Chinese Taipei

Thailand

Total land area – 515,357 km^2

Population - 65,068,149

Marginal lands - 17,253 km^2 (3.3% of total area)

Biomass resource potential on marginal lands – 10,394,000 tonnes/year

Ethanol potential from marginal lands – 4 hm^3 (38% of current gasoline consumption)

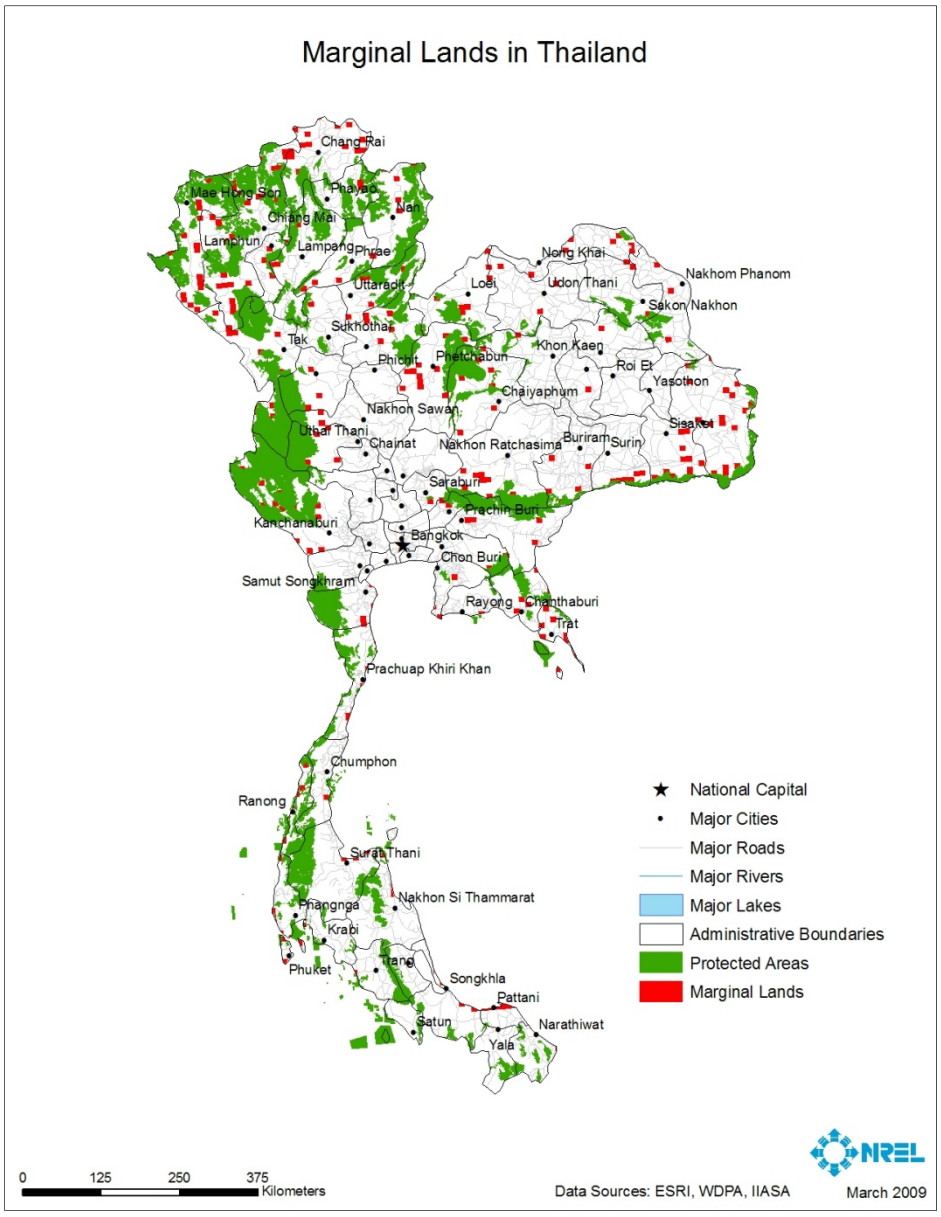

Figure 21 Marginal Lands in Thailand

United States

Total land area – 9,426,295 km^2

Population - 301,139,947

Marginal lands - 1,214,007 km^2 (13% of total area)

Biomass resource potential on marginal lands – 377,413,000 tonnes/year

Ethanol potential from marginal lands – 148 hm^3 (19% of current gasoline consumption)

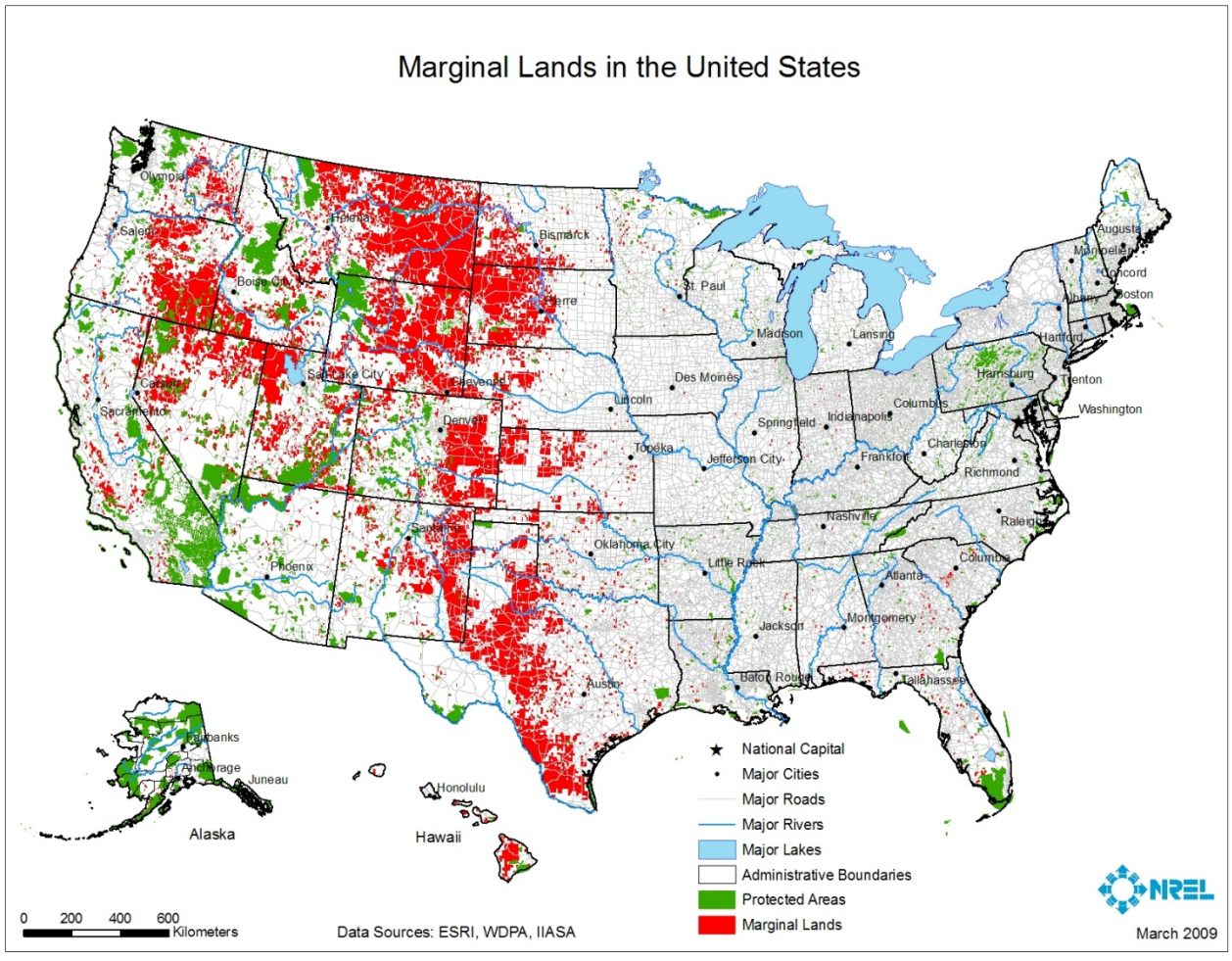

Figure 22 Marginal Lands in the United States

Viet Nam

Total land area – 322,743 km^2

Population - 85,262,356

Marginal lands - 21,090 km^2 (6.5% of total area)

Biomass resource potential on marginal lands – 11,281,000 tonnes/year

Ethanol potential from marginal lands – 4.4 hm^3 (79% of current gasoline consumption)

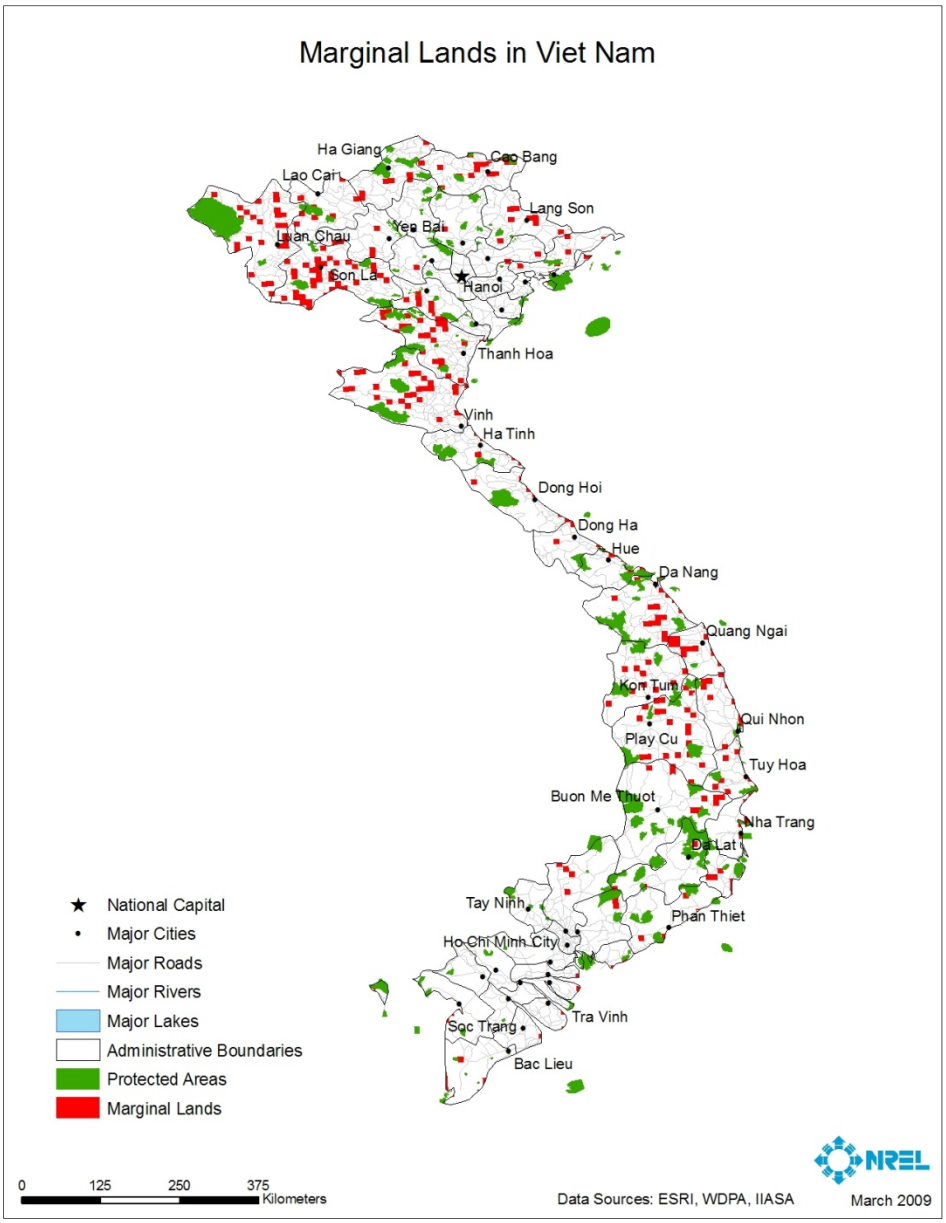

Figure 23 Marginal Lands in Viet Nam

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APEC#209-RE-01.4