ESTIMATION OF GLOBAL ARABLE AND IRRIGABLE LAND USING GIS

by

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Abstract

As part of a study to determine the history and potential for conflict in international freshwater basins, an estimate was made of the location of arable and irrigable land in the world. Knowledge about the world's arable and irrigable land was desired since this information could be an indicator of the potential for water resources development in a nation. This study's approach to estimating arable and irrigable land was an improvement over previous approaches in that relatively new information sources (satellite imaging) and techniques (geographic information systems) were used in the analysis. The analysis showed that, on the continent scale, the amount of land currently under crops and the amount of land currently irrigated were a small percentage of the estimated arable and irrigable land, respectively. Also apparent from the analysis was the fact that significant refinements in the resolution of the spatial data are needed in order for accurate estimates of arable and irrigable land to be made.

Keywords: global arable land, global irrigable land, GIS, water development, international freshwater basins, water conflict

Introduction

This paper describes an analysis undertaken as part of the Basins at Risk (BAR) Project at Oregon State University Department of Geosciences. The objective of the BAR project was to characterize the cooperation and conflict between sovereign states sharing international freshwater basins and, based on the historical record of conflict and cooperation, determine which characteristics are strong indicators of the potential for cooperation and conflict within shared basins. Using these indicators, the international basins at potential risk for future conflict over freshwater resources were identified.

An important part of the BAR project was the study of the potential for water resources development within a nation and how this development might affect the level of cooperation and conflict within a shared basin. One indicator of a nation's potential for water resources development is the amount of land that is both arable and irrigable. A related parameter is the proportion of arable and irrigable land that contains irrigated agriculture. If a nation has large areas of unused irrigable land and were to convert these areas to irrigated farmland, the additional water demands could be significant. Any diversions from an international water body might cause conflict with other riparian nations and would, therefore, be relevant to the BAR study. The BAR project team decided to include an estimate of the arable and irrigable land within each of the world's international basins.

Ideally, estimates of the world's arable and irrigable land would have been in a digitized form ready for processing by the BAR geographical information system. Unfortunately, a current estimate of global arable and irrigable land is not available in any form. While estimates of the world's arable land have been made in the past and mapped (Grigg 1993, 93), they were often based on incomplete information and, at best, relied on informed guesswork by panels of experts. The only map of global arable land found during this research was one shown in The World Food Problem (Grigg 1993, 97), which was attributed to the 1968 Times Atlas of the World. However, a review of this atlas showed no such map. In addition, the map presented by Grigg shows most of South America, Africa, and even a good portion of middle North America as not containing arable land – which is highly improbable. With advances in satellite imaging and geographic information systems, much more spatial information on land characteristics is currently available. This paper describes an attempt to use this spatial information to estimate the world's arable and irrigable land.

Methodology

The approach used in this study was to initially consider all global land arable and irrigable and to systematically eliminate land that met specific criteria, i.e., conditions that caused the land to be unsuitable for agriculture and/or irrigation. Once the spatial data were collected and transformed into a usable format, a geographical information system (GIS) was used to perform the analysis. The estimate of global arable and irrigable land did not include Antarctica or Australia, since these continents, which do not contain international basins, were not included in the BAR study.

Data Sets

The Arc/Info and Arc/View GIS programs from ESRI were used to analyze elevation, slope, land cover, soil degradation, soil type, climate, and irrigated area data sets. The digitized, gridded data sets are summarized in Table 1. Because the resolution among the data sets was not uniform, the analysis was constrained by the coarsest resolution, i.e., one degree. This is equivalent to about 110,000 meters in the Lambert equal area world projection. The general approach for the analysis was to use a series of spatial screens to filter out, or eliminate, based on physical characteristics, the land areas that are unsuitable or impractical for agricultural use or irrigation. An estimate of arable and irrigable land was made for each continent (except for Australia and Antarctica), and the results were combined to create a global estimate.

The U.S. Geological Survey, the University of Nebraska-Lincoln, and the European Commission's Joint Research Centre jointly developed the global land cover data set (USGS GLCC). A display of this data set is presented in Figure 1. The land cover characteristics are aggregations of seasonal land cover patterns based on 30 arc-second Advance Very High Resolution Radiometer (AVHRR) data obtained from April 1992 through March 1993 (U.S.G.S). The NASA Goddard Institute for Space Studies has produced a global map of FAO soil types, which is presented in Figure 2. This data set is intended primarily for global climate modeling (Zobler 1986). Figure 3 shows the results from the International Soil Reference and Information Centre's (ISRIC) Global Assessment of the Status of Human-induced Soil Degradation (GLASOD). ISRIC was commissioned by the United Nations Environmental Programme (UNEP) to produce a scientifically credible global assessment of the status of human-induced soil degradation. The objective was to provide decisions makers with some knowledge about the risks resulting from inappropriate land and soil management. Figure 4 presents the global extent of the twelve major Koppen climate zones. For the purpose of global modeling of water use and crop production, a digital global map of irrigated areas was developed by Döll and Siebert (1999). The map, presented in Figure 5, depicts the areal percentage of each 0.5-degree cell that was equipped for irrigation in 1995. It was derived by combining information from large-scale maps with outlines of irrigated areas (one or more countries per map), and U.N. FAO data on total irrigated area per country in 1995.

Estimate of Arable Land

The USGS GLCC database was used to make an initial estimate of potential agricultural land in the world. Potential agricultural land was considered to be all land except urban and built up areas, water bodies, tundra, and snow or ice. Land that has a slope greater than 30%, based on the USGS Landscan global slope data, was also eliminated. The 30% value was determined to be the maximum terrain slope at which agriculture could succeed (Marsh 1978, 66). Land areas characterized as wasteland in the ISRIC Global Soil Degradation grid (active dunes, salt flats, rock outcrops, deserts, icecaps, and arid mountain regions) were determined to be unsuitable for agriculture and were eliminated from consideration. A review of the available soil literature showed that, while many soil types require modifications in order to be suitable for agriculture, only one soil type, lithosols, is considered to be generally unsuitable (FitzPatrick 1986, 102) Lithosols are the shallow soils of mountainous areas, fairly recent volcanic flows, and areas scraped by bare ice and have little potential for crop production. Accordingly, land areas where the GISS soil unit database indicated that the predominant soil type is lithosols were also eliminated from consideration.

The USGS GLCC database was used to determine the actual agricultural land in the world. Actual agricultural land was considered to be dryland cropland and pasture, irrigated cropland and pasture, mixed dryland/irrigated cropland and pasture, cropland/grassland mosaic, and cropland/woodland mosaic. These areas are shown in Figure 6. The land areas remaining from the initial filter of potential agricultural land were compared to the current agricultural land, as described above, in the USGS GLCC database. Any areas that were initially eliminated, but in which the USGS GLCC database indicated the presence of agricultural activity, were added back into the set of potential agricultural land. At this point in the analysis there existed two gridded data sets – an initial estimate of the extent of potential agricultural land and the extent of actual agricultural land in the world.

The next step in the analysis was to determine the maximum elevation for potential agricultural activity within the specific climate zones found in each continent. A gridded map of the major Koppen climate zones was used. All land areas in the icecap (arctic) and tundra climate zones were considered unsuitable for agriculture. The maximum elevation in each climate zone at which agriculture is actually occurring, based on the GLCC database, was determined. The initial estimate of the extent of potential agricultural land was then refined to include only areas located below the maximum elevation at which agriculture within each climate zone was actually occurring. The result was a gridded data set containing an estimate of the potential agricultural, or arable, land in each continent. The results for each were combined to create an estimate of global arable land. The final results are shown in Figure 7.

Estimate of Irrigable Land

Irrigable land was considered to be all arable land that was determined to be suitable for irrigation. Countries were categorized as "developed" or "undeveloped" with regards to irrigation potential. The designation of countries as developed or undeveloped was based on the World Development Report 1996 (World Bank 1996, 238). Undeveloped countries were those classified as "low-income" in the report, based on GNP per capita. An assumption was made that "middle-income" countries would have access to similar irrigation expertise and technology as "high-income" countries, whereas "low-income" countries might not. Slope values of 15% for developed countries and 5% for undeveloped countries were used as the upper limit for irrigable land (Jackson 2000). The resulting grid contained an initial estimate of the irrigable land in the world. This map was compared to the currently irrigated areas of the world found in the Global Map of Irrigated Area. Any areas that are currently irrigated but were not contained in the initial estimate were then added. The result was a final estimate of the irrigable land in the world and is shown in Figure 8.

Discussion of Results

The Basins at Risk project has created GIS coverages of the world's international river basins, i.e., those shared by two or more sovereign states. These coverages and the coverages produced by this study were used to estimate the arable and irrigable land within each one of the international basins of the world, and the percentage of the arable and irrigable land that is actually used for these purposes. The goal was to determine if these parameters are indicators of cooperation and conflict between riparian states and, if so, how much influence they have on the amount of cooperation and conflict. The GIS was used to determine the amount of arable and irrigable land in each international basin. Unfortunately, the results were not of much use because of problems caused by the one-degree cell resolution. The small size of some basins (less than 1000 sq. km) and the inclusion of entire edge cells in the area calculations caused the estimates of arable and irrigable land in many basins to be greater than the actual land area in those basins. Although this problem could have been overcome by breaking the arable and irrigable land grids into more refined grids, doing so would have implied greater accuracy in the results than was possible from the input data. While the one-degree resolution used in this study might be too crude for detailed analysis, the gridded data produced might be useful in comparing different regions. In a study such as the Basins at Risk project, these types of comparisons could give insight into the different characteristics of the world's international river basins.

Table 2 shows the results from this research*. The land currently under irrigation includes only the 0.5-degree grid cells where the irrigated land area is at least 10% of the total area in the cell. Only a small proportion of the irrigable land in the world is actually irrigated. Clearly, however, much of the land in the world that is physically suitable for irrigation does not need to be irrigated because of adequate and reliable precipitation. Filtering through a climate grid containing detailed information on precipitation could refine the global irrigable land grid. This would produce a data set containing irrigable land areas where irrigation is actually necessary. Another way to refine the estimate of irrigable land would be to use a filtering grid containing land areas that could realistically be served by the world's current water distribution systems. This would give an indication of the practicality of irrigating particular land areas.

The estimate of arable land includes much more land area than is currently under crops. This might indicate that land that is theoretically arable is not able to be cultivated in any practical way. If the analysis had included non-physical factors such as technological and economic

* The results from the analysis described up to this point are contained under "Part A" in Table 2. The results contained under "Part B" are described later in the paper.

development, the estimate of arable land would have reflected such limitations and would probably have been much less. Even though a nation might have large areas of arable and irrigable land, this land will remain non-agricultural if there is no practical way to farm it or deliver water to it. Unrealized agricultural potential could also be due to political as well as technological or economic barriers. Although political, technological, and economic factors are extremely important in determining the practical availability of arable and irrigable land, their inclusion was beyond the scope of this study.

Unrealized agricultural potential might also be evidence that a country or region is growing enough food to satisfy its internal needs and exports, rather than an indication of some kind of failure in planning or policy. This is particularly true in the wealthier countries of the world. As agricultural technology advances, less land is needed to satisfy a country's food demands. Also, a country that obtains wealth from industries besides agriculture can use international trade rather than domestic agriculture to feed its people. However, in the world's poorer countries where widespread hunger is often a serious problem, the conversion of unused agricultural land to cropland might be the most economical way to alleviate hunger.

Table 2 also compares the estimates of arable land obtained from this study (Part A) to those obtained in other studies. In 1988, the U.N. Food and Agriculture Organization (FAO) published estimates of current agricultural land in the world (FAO 1988). The FAO's estimates of the percentage of land in each continent currently used for agriculture are generally less (except for North America) than the estimates obtained from the GLCC land cover database. In 1967, the President's Science Advisory Committee (PSAC-1967) estimated the proportion of total land in each continent that is arable land (President's Committee 1967, 434). The PSAC estimates are generally about one-half of those obtained from this research project. The focus of the PSAC analysis was on quantifying the amount of arable land rather than on its spatial distribution. Therefore, although PSAC used spatial data in the form of land use, soil, and climate maps to determine the amount of arable land in world, it did not produce a final map that showed the location of this arable land. Even without the benefit of modern remote sensing techniques and GIS data, it appears that the PSAC had access to more refined data with regards to global soil distribution (in map form) than was available for the study described in this paper. Because soil characteristics are extremely important in determining agricultural suitability and the resolution of the gridded soil data used in this study were relatively course, the accuracy of the arable land estimate was severely limited.

This analysis was limited by the resolution of the data sets that were available. The least refined data sets were the ones that contained soil type and climate information. The resolution of the grids for these data sets was one degree, which is equivalent to about 110,000 meters in the Lambert equal area world projection. The most refined data sets were those that contained elevation, slope, land cover, and soil degradation data (converted from polygons), having a resolution of 30 arc-seconds (1000 meters). Since analytical results that were more refined than the least refined data set could not be presented with confidence, the cell size for the output grids was chosen to be one degree. This meant that the more refined gridded data had to be converted into one-degree cells containing spatially-averaged values. The most significant impact of this might have been on the estimation of irrigable land, which was heavily dependent on the slope of the land surface. The percentage of arable land determined to be irrigable is probably overestimated in Part A. This overestimate was due to the loss of resolution in converting the 30 arc-second data grids to one-degree grids, since the averaging routine in ARC INFO assigned the one-degree cells the average values for the roughly 10,000 original 1000-km cells that comprised the each-one degree cell. For example, isolated, highly sloping terrain was lost in the averaging procedure because it was "outweighed" by more prevalent, gently sloping terrain.

In order to estimate how the results were affected by using one-degree cells rather 30 arc-second (one-kilometer) cells, an alternative analysis was completed. The basic approach was the same, except that only the data sets containing the 30 arc-second cells were used (i.e., land cover, slope, and soil degradation). As was done in the first analysis, arable land was estimated by selecting potential agricultural land from the GLCC database and eliminating land areas having slope greater than 30% or designated as wasteland in the GLASOD database. Irrigable land was determined to be any arable land with slope values less than 15% or 5%, depending on whether the country containing the land was "developed" or "undeveloped", respectively. The goal of this second analysis was to determine how much, if any, accuracy was gained by using a larger number of data sets at relatively course resolution compared to using a lesser number of data sets at more refined resolution.

Figures 9 and 10 show the results from the alternative analysis (Part B) used to estimate global arable and irrigable land. In these figures, the icecap and tundra climate zones have been masked out since land areas in these climate zones were eliminated entirely in the first analysis (Part A). While this might appear to contradict the decision to perform the analysis using a uniform spatial resolution for all data sets, it helps visually when comparing the results from the two analyses. A comparison of Figures 9 and 10 to Figures 7 and 8 does not reveal a noticeable difference in the areal extent of the arable and irrigable land estimates. The results from the two analyses are also presented in Table 2. The percentage of total land that is arable land was greater in Part B for all continents, with a difference ranging from 2.9% for Africa to 29% for Asia. The large difference for Asia and North America (21%) was due primarily to the relatively large area of these continents that is within the tundra climate zone. Although tundra land is masked out in Figures 9 and 10, arable lands in this climate zone (and icecap) are still included in the final estimate for Part B. The fact that the difference in results between the Part A and Part B analysis was so small for Africa, where there is virtually no tundra or icecap, indicates that using climate and soils data (at least at one degree resolution) does not improve the accuracy of the results. This is also shown by comparing the estimates for the percentage of arable land that is irrigable land in Table 2, where the results from Part A and Part B do not differ significantly for any continent.

While the preceding small-scale comparison showed that the accuracy of the results did not appear to change significantly by using a smaller number of finer resolution data sets, a large-scale comparison shows that the precision improved considerably. Figure 11 shows a detailed view of the arable land estimates for Part A and Part B for the central Pacific coast of South America. It is clear from this map that the analytical approach used in Part B was able to precisely eliminate the highly-sloping mountains of Andes Mountains and the barren wastelands of the Atacama Desert. The lack of precision exhibited by the Part A analysis is evidenced by the crude patchwork of one-degree cells representing arable land. The large areas of the Andes Mountains not included in the Part A arable land estimate were probably eliminated during the analytical step of selecting land within each climate zone below the maximum elevation of current agricultural activity (this step was not performed in the Part B analysis).

Figure 12 shows a large-scale view of the Part B irrigable land estimate for east-central Africa. While this map also clearly shows the precision of the Part B analysis, it is of more interest because of the spatial pattern of some of the non-irrigable land. Very clearly delineated are the large inland water bodies, the Niger-Benue river system in the middle of the map, and the Congo river system near the low right part of the map. The latter two are an artifact of the GLCC land cover database, where cells along waterways are assigned no value. This artifact is transferred throughout the analysis and manifests itself in the Part B arable and irrigable land estimates. This is an unfortunate gap in the GLCC data since a good amount of agricultural activity occurs along the flat land along the world's rivers.

Improvements in the data sets for soil types and climate are needed in order to make accurate and precise estimates of the world's arable and irrigable land. With regards to the analytical approach used in this study, climate classification is the more important of these two data sets since it was a fundamental component of the analysis. This study relied on the Koppen classification system to delineate the climate regions for each continent. While the Koppen system is extremely useful as a teaching tool, because it represents the world's climate variability in general and easily understood terms, it is not usually recommended for analytical research (Rumney 1968, 107). This is because it does not accurately portray the variation within regions and, more importantly, the subtle differences at the boundaries between regions. However, it was the only digitized climate classification system available for use in this study. Therefore, the

Koppen system was an acceptable data set to use during this initial attempt at determining arable land.

While the Koppen classification system uses temperature and precipitation distribution to try to show variations within climate zones, it is essentially phytographical since it is uses vegetation distribution as a basis for delineating the major climate zones (i.e., tropical forest, dry, mesothermal forest, microthermal snow forest, and polar). Koppen's justification for this approach was that climatic characteristics are closely linked to dominant vegetation types (Rumney 1968, 104). Since vegetation types rarely exhibit distinct boundaries, basing a climate classification system on their distribution inevitably leads to boundary problems. This might be why a one-degree grid is the most refined grid available for this type of spatial information. As an alternative, the system proposed by Thornwaite might be more appropriate for the type of analysis used in this study. Thornwaite's system uses a precipitation effectiveness index (PEI) that incorporates precipitation and potential evaporation values at specific locations (Thornwaite 1948, 55). The primary advantage of this system is that it is independent of vegetation, soils, or other physical parameters. While a major obstacle to wider use of the Thornwaite system has been its relative complexity, it has been shown to have practical value in agricultural applications (Lydolph 1985, 184). The tens of thousands of weather stations around the world probably contain enough data to derive a comprehensive grid of PEI values, which could be processed by a GIS. The output could be a refined (30 arc-second), regular grid of climate zones in which desired ranges of PEI values are represented. If these PEI zones were used instead of the Koppen climate zones, the estimate of global arable land would probably be much more refined. Until recently, the derivation of a gridded climate classification map of the world based on the

Thornwaite system was not possible without the use of expensive computer equipment and software. However, such a task could be done relatively quickly with current GIS software and computer hardware. The major obstacle would probably be the availability and collection of the raw data.

Although the results of this analysis were intended for use in assessing the potential for water conflict, they could be used for other applications as well. Agricultural planners could certainly be helped by information on the suitability of particular land areas for agriculture and irrigation. However, to be useful for this purpose, the results would need to be greatly refined. Not only would the resolution of the results need to be increased (e.g., 1 km grid cells), the arable/non-arable and irrigable/non-irrigable designation would need to be replaced with a range of values. These values would need to reflect the physical, political, social, and economic suitability of each grid cell for agriculture and irrigation. The Global Assessment of Human Induced Soil Degradation (GLASOD) data contains additional descriptive attributes besides the type of degradation. GLASOD also describes the degree of soil degradation (light to extreme) and extent of soil degradation (as a percentage of land area affected) for the world's land areas. This type of information could be used to further refine the estimate of arable land by establishing maximum allowable values for the degree and extent of different types of soil degradation. If land areas were found to have soil degradation above these values, those areas could be designated as non-arable and/or non-irrigable. The degree and extent of soil degradation could also be used to determine the relative level of agricultural and irrigation potential for land areas.

With the ever-improving capability in GIS data collection and storage, the availability of non-physical parameters and indicators in the form of digitized spatial data sets should increase. As this happens, geographic analysis relying on both physical and non-physical information will become more accurate. In the future, there should be an improvement in the quality and detail of the data that were used in this study. When this occurs, the methodology used here should be repeated in order to get a more refined estimate of the world's arable and irrigable land.

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Table 1. Data Set Descriptions

Data Set Description	**Source of Gridded Data**	**Grid Resolution**
Elevation	USGS Continent Digital Elevation Model –from Global Land Information System, EROS Data Center. (edcwww.cr.usgs.gov)	30 arc second (1000 m)
Slope	USGS Global Slope Data from Landscan	30 arc second (1000 m)
Land Cover	USGS Continental Land Cover Data from Global Land Cover Characteristics (GLCC) database	30 arc second (1000 m)
Soil Type	GISS Global FAO Soil Units from the NASA Goddard Institute for Space Studies (GISS)	1 degree
Soil Degradation	ISRIC Global Soil Degradation from the United Nations Environment Programme, produced by the International Soil Reference and Information Centre (ISRIC)	1 degree from polygon coverage

Climate	Global Koppen Major Climate Zones (1 degree cell size) from FAO's Environment and Natural Resources Service (SDRN) global climate maps series. - FAO-SDRN Agrometeorology Group – 1997. http://www.fao.org/sd/eidirect/CLIMATE/Eisp0001.htm	1 degree
Irrigated Area	Global Map of Irrigated Area from Petra Doll's web page (http://www.usf.uni-kassel.de/english/personal/petra_doell_eng.htm).	0.5 degree

Table 2. Arable and Irrigable Land.

Continent	Percentage of Total Land Currently Used for Agriculture		Percentage of Total Land that is Arable Land			Percentage of Arable Land that is Currently Used for Agriculture		Percentage of Arable Land that is Irrigable Land		Percentage of Irrigable Land that is Currently Irrigated	
	This Analysis	**FAO-1988**	**Part A**	**Part B**	**PSAC -1967**	**Part A**	**Part B**	**Part A**	**Part B**	**Part A**	**Part B**
Africa	7.3%	6.7%	65.5%	67.4%	24.2%	11.1%	10.8%	95.7%	93.3%	1.2%	1.2%
Asia	20.6%	16.7%	52.6%	68.0%	22.9%	39.2%	30.3%	91.5%	93.8%	5.9%	4.5%
Europe	52.4%	18.7%	75.4%	80.5%	36.4%	69.5%	65.1%	96.4%	96.4%	8.2%	7.6%
North America	8.8%	12.2%	44.3%	53.5%	22.0%	20.0%	16.5%	97.5%	96.1%	3.9%	3.2%
South America	25.9%	8.9%	78.3%	87.4%	38.8%	33.0%	29.6%	98.8%	97.5%	1.5%	1.3%

FIGURES

Figure 1 - Global Land Cover Characteristics

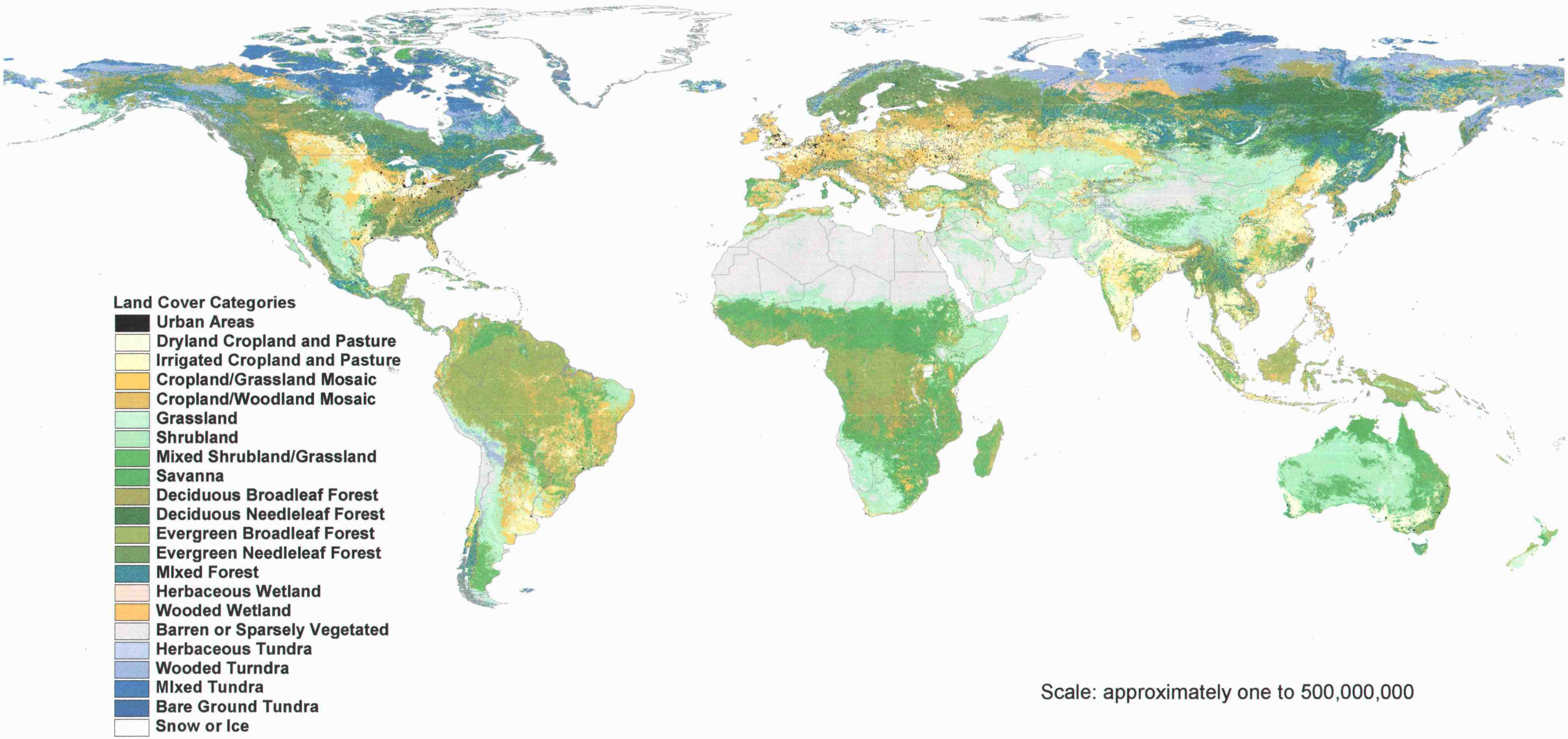


Figure 2 - Distribution of Soil Types Throughout the World

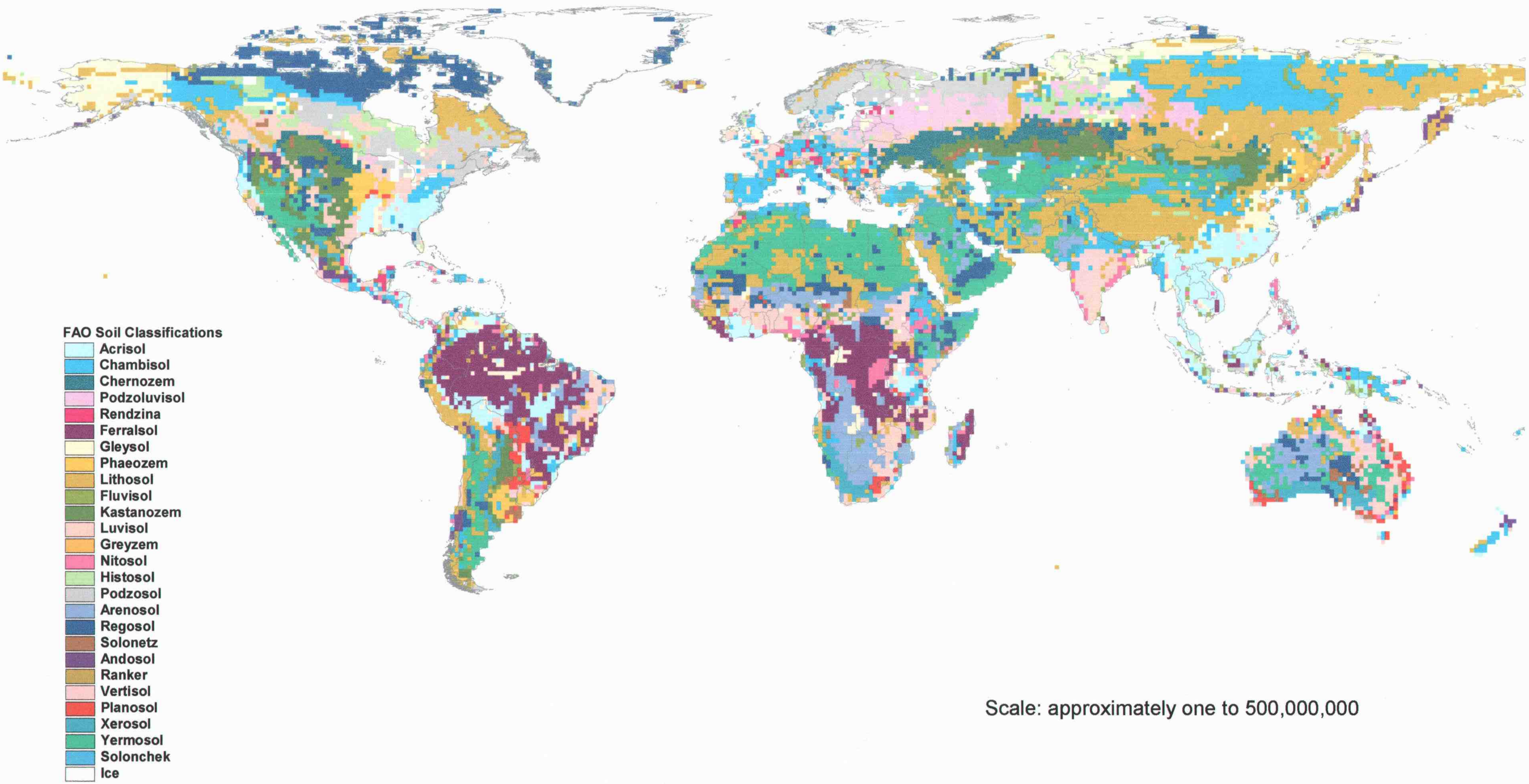


Figure 3 - Global Soil Degradation

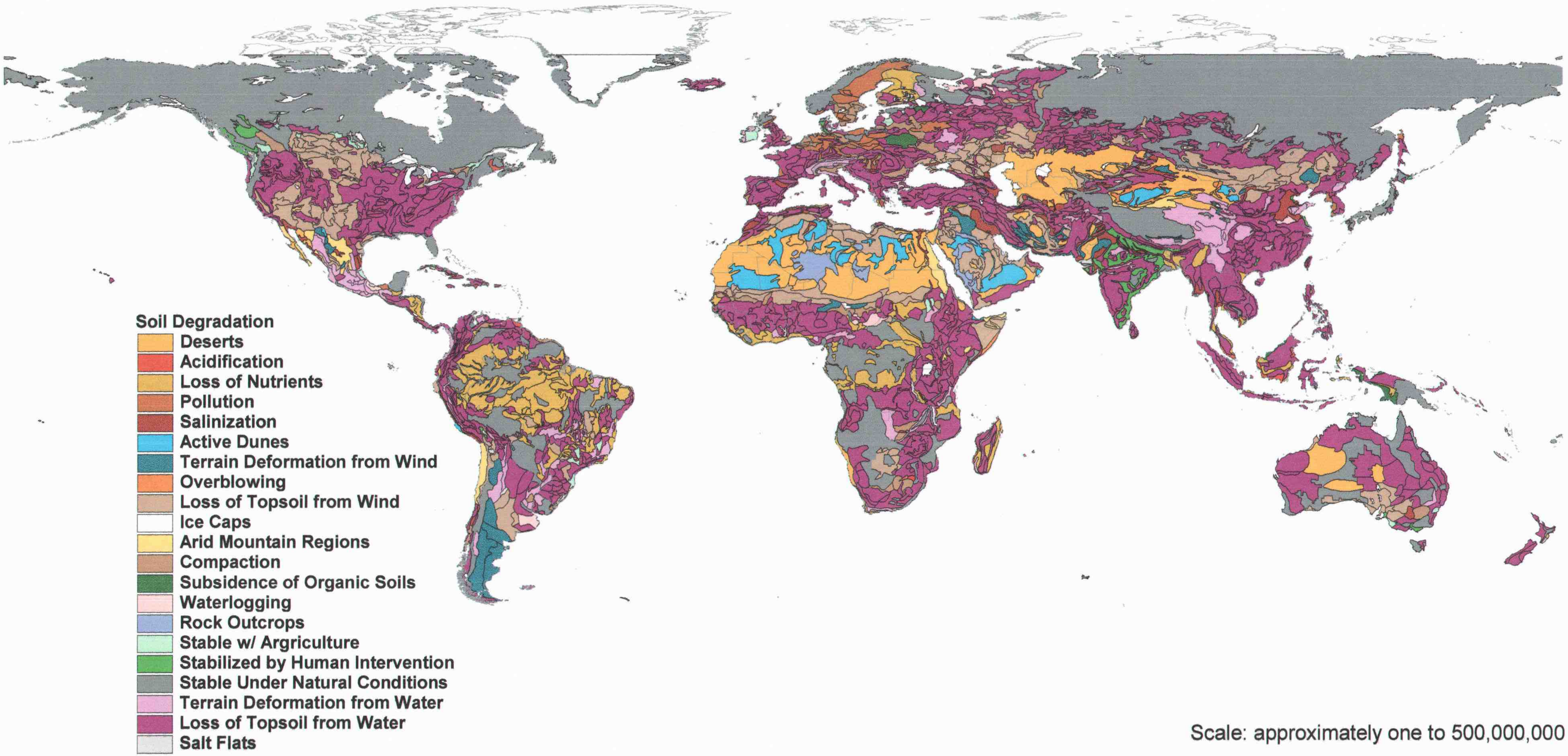
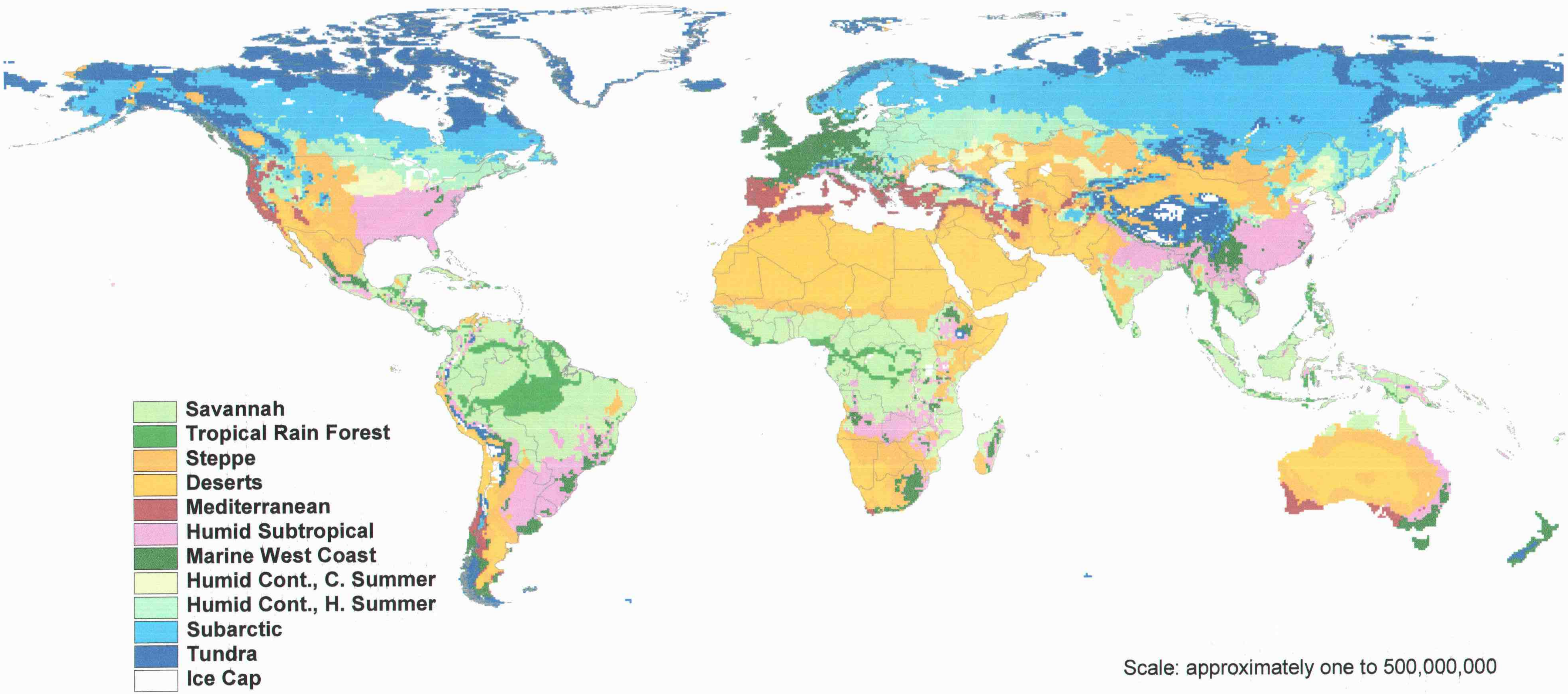
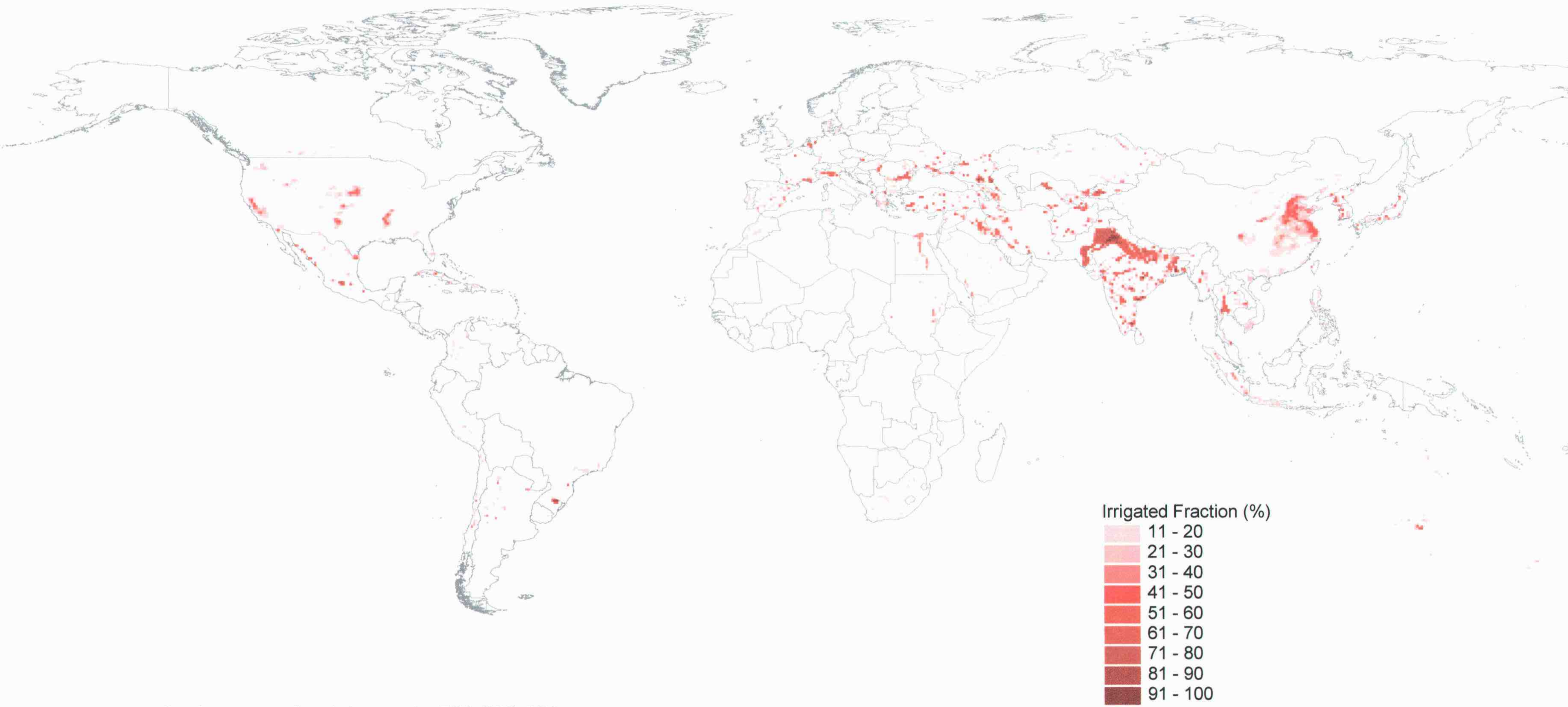


Figure 4 - World Climate Zones



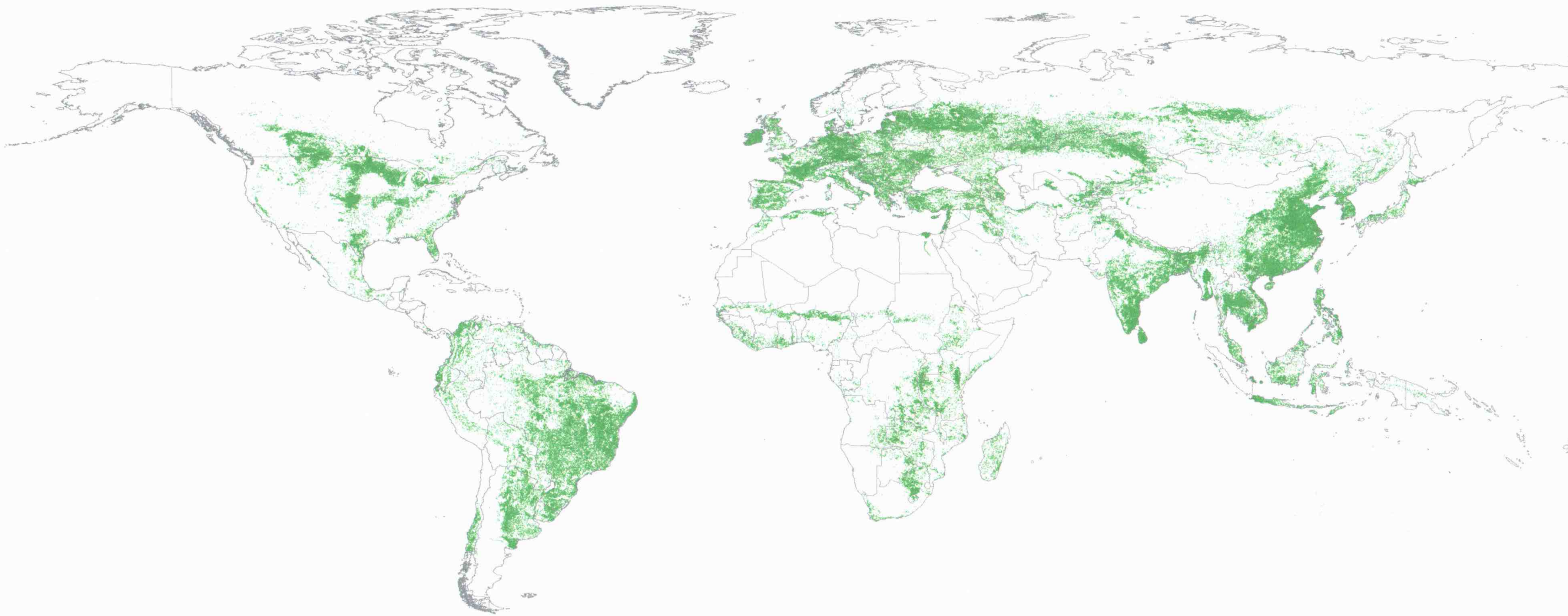
Scale: approximately one to 500,000,000

Figure 5 - Irrigated Land of the World
(Where irrigated area is greater than 10% of the total land area)



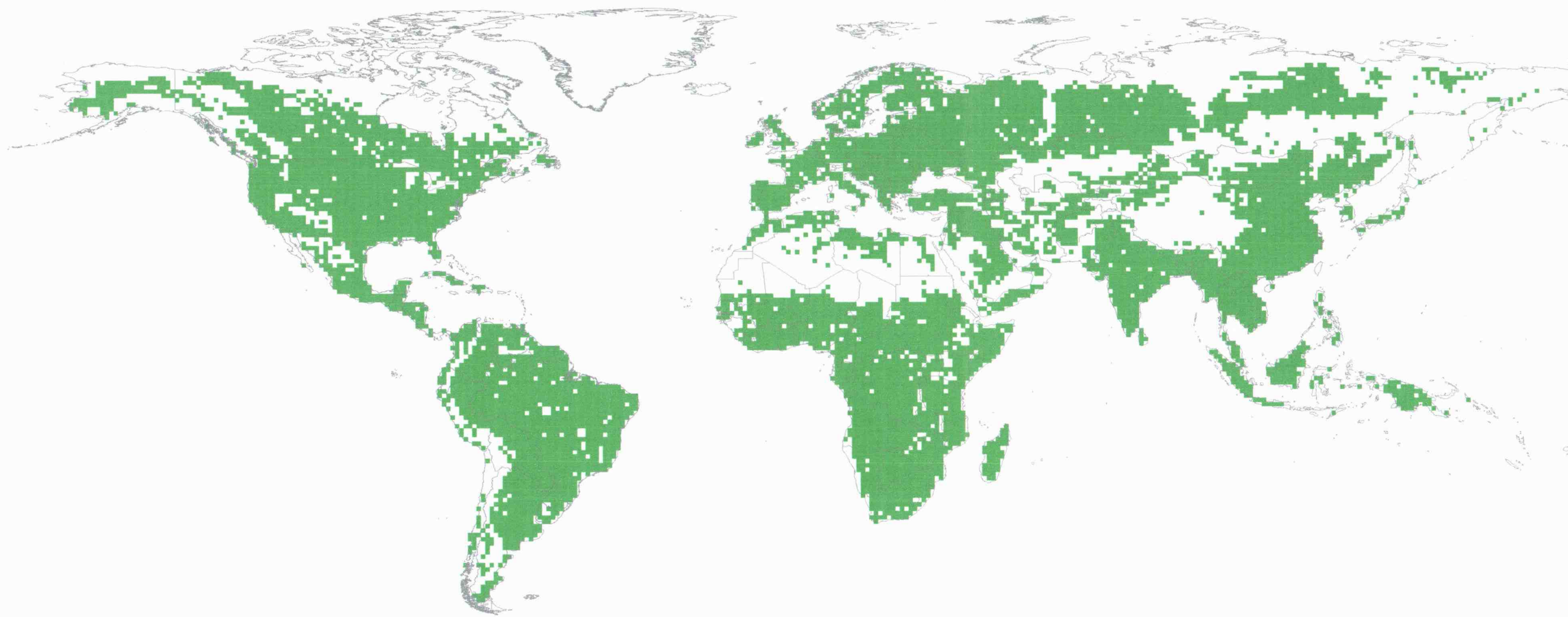
Scale: approximately one to 500,000,000

Figure 6 - Estimate of Current Agricultural Land



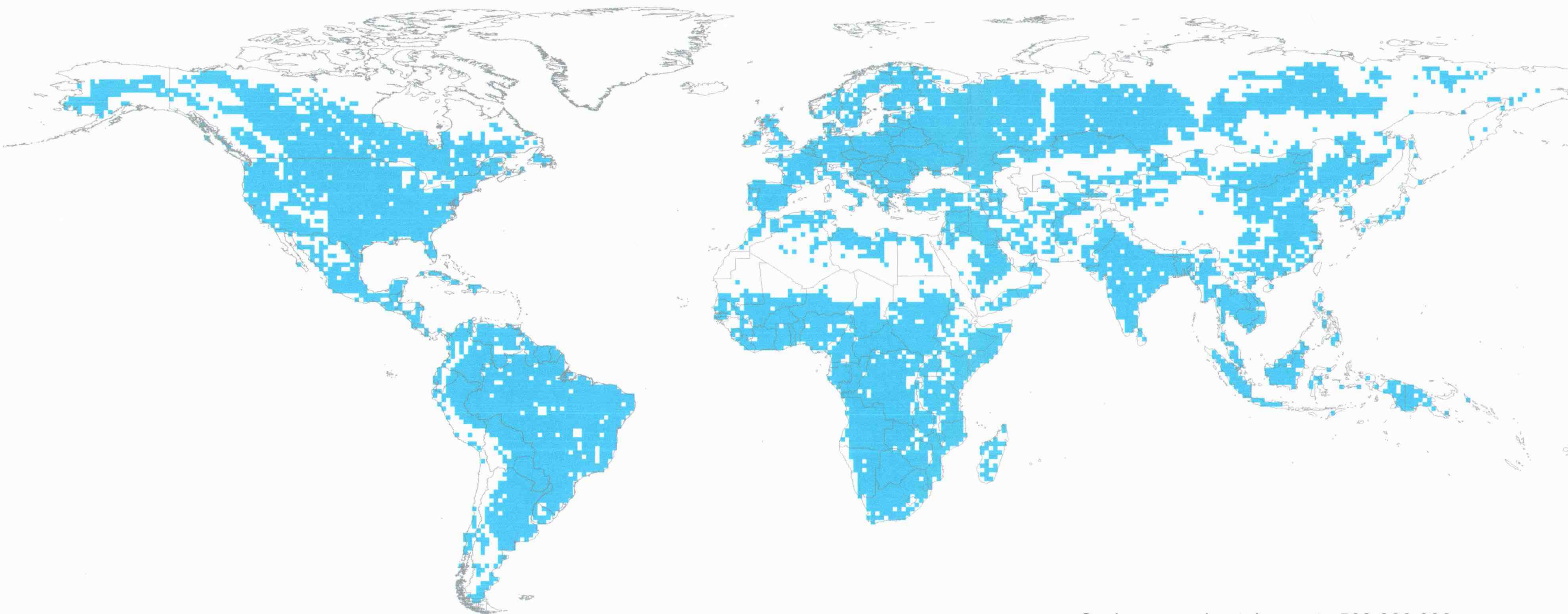
Scale: approximately one to 500,000,000

Figure 7 - Estimate of the World's Arable Land



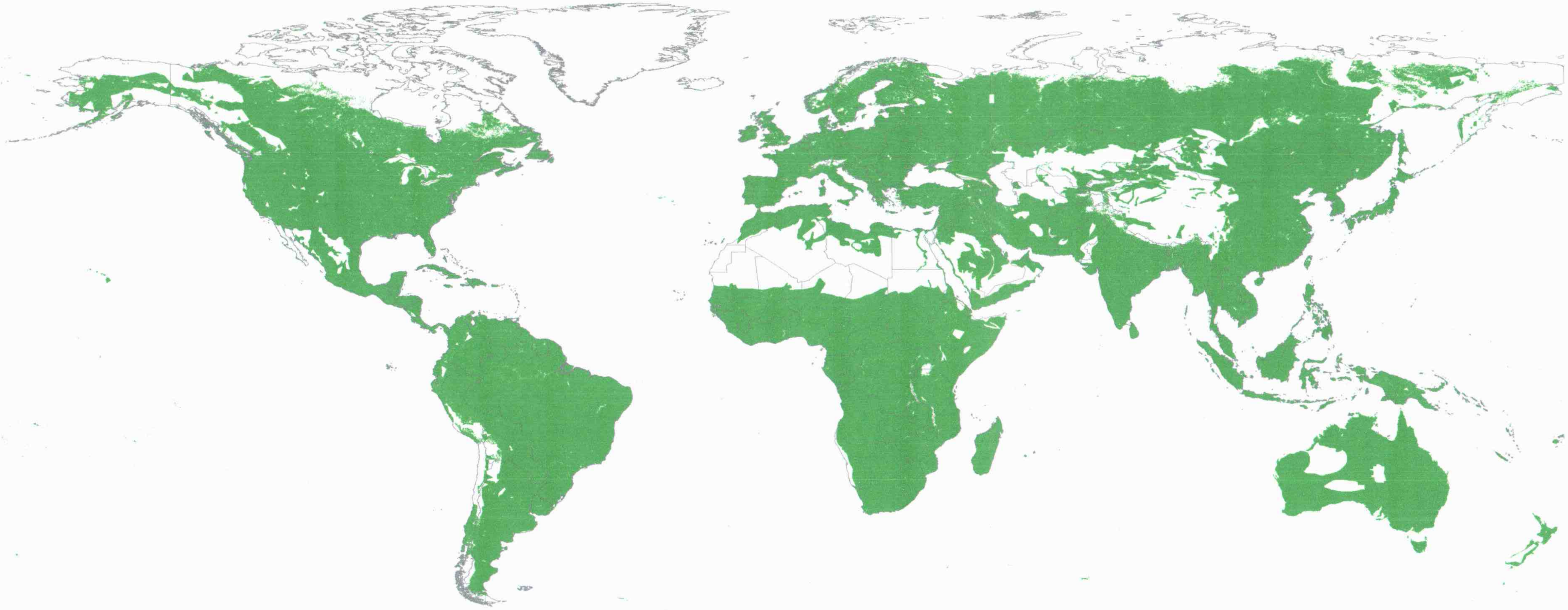
Scale: approximately one to 500,000,000

Figure 8 - Estimate of the World's Irrigable Land



Scale: approximately one to 500,000,000

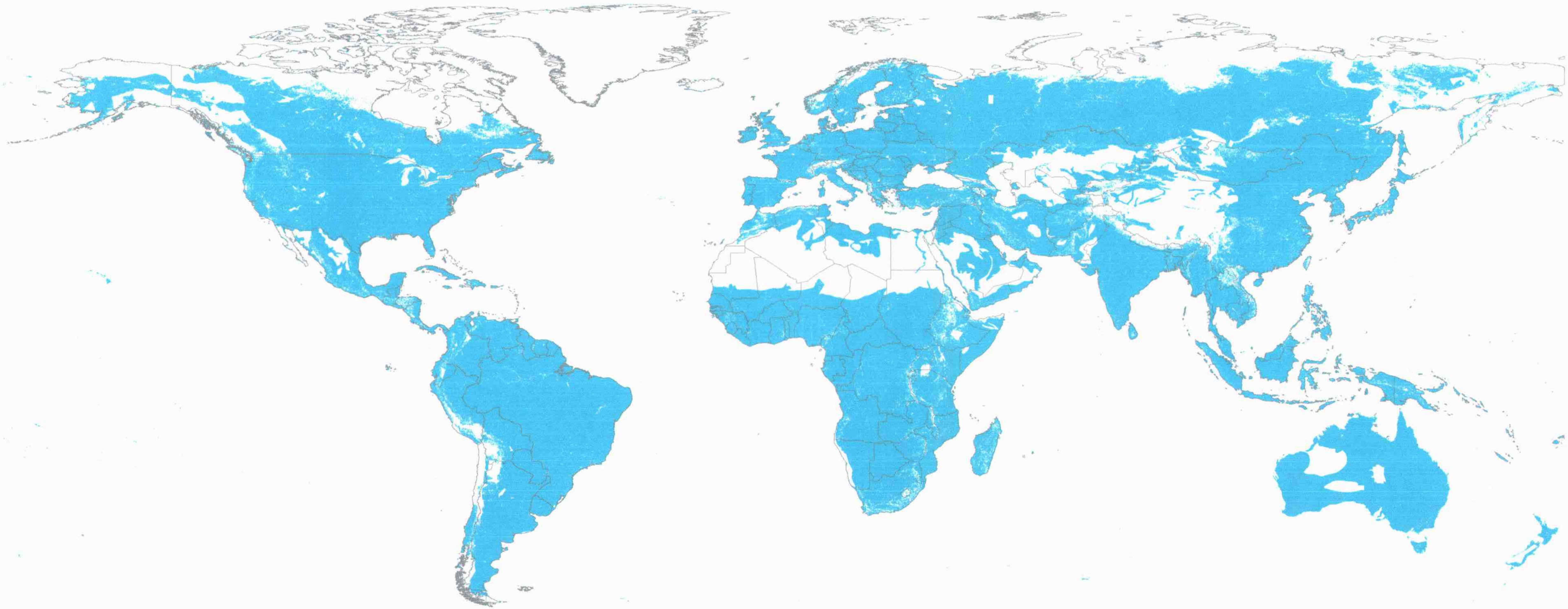
Figure 9 - Estimate of the World's Arable Land
(based only on land cover, soil degradation and slope*)



* note: icecap and tundra climate zones masked out.

Scale: approximately one to 500,000,000

Figure 10 - Estimate of the World's Irrigable Land
(based only on land cover, soil degradation and slope*)



* note: icecap and tundra climate zones masked out.

Scale: approximately one to 500,000,000

Figure 11 - Comparison of Part A and Part B Results

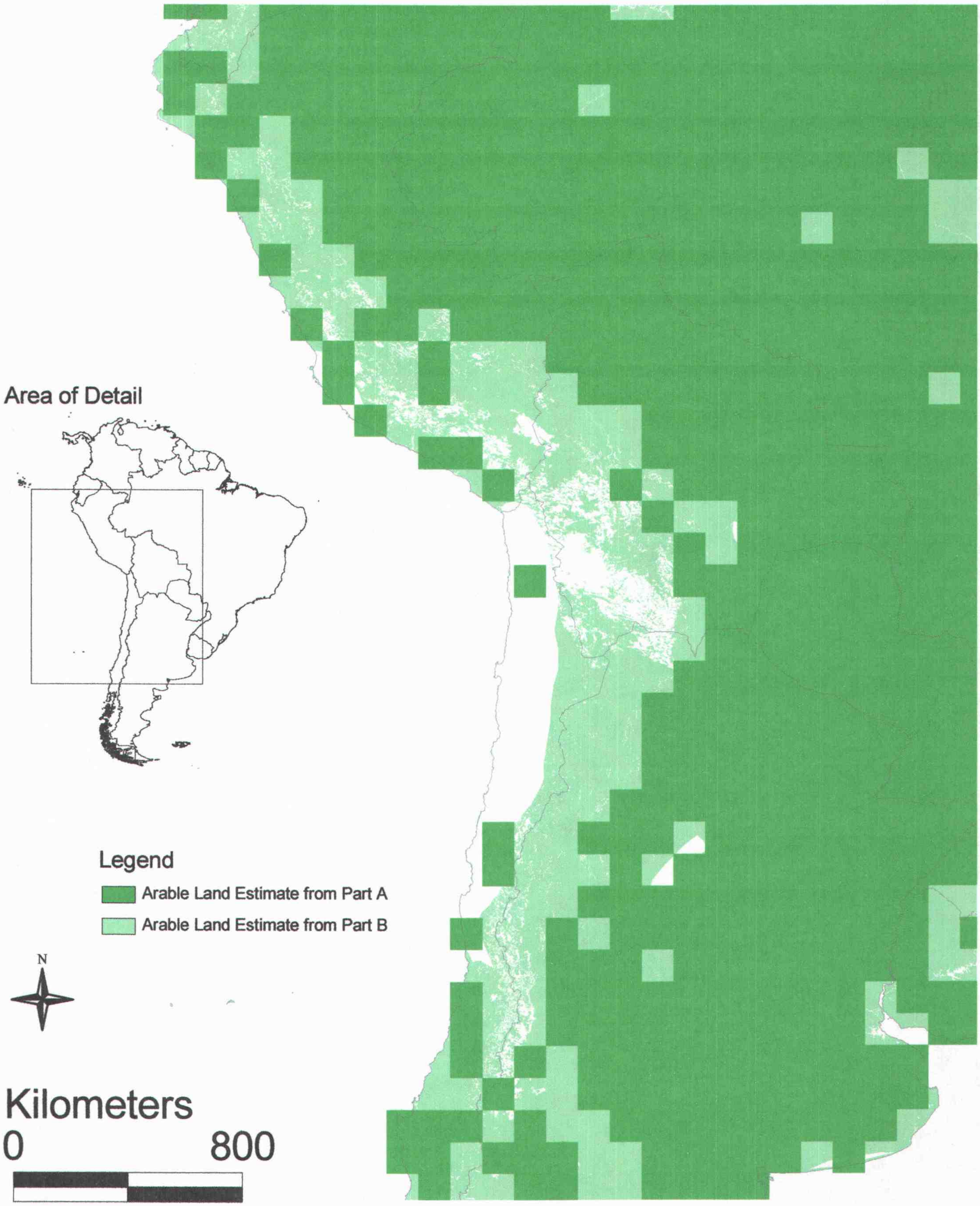


Figure 12 - Detailed View of Irrigable Land in Africa (based only on land cover, soil degradation, and slope)