Anuário do Instituto de Geociências - UFRJ
www.anuario.igeo.ufrj.br

Soil Erosion and Conservation in Brazil

Erosão e Conservação de Solos no Brasil

Antônio José Teixeira Guerra[1]; Michael A. Fullen[2];
Maria do Carmo Oliveira Jorge[1] & Silvia Teixeira Alexandre[1]

[1] Universidade Federal do Rio de Janeiro, Departamento de Geografia,
Av. Athos da Silveira Ramos, 274, CCMN, 21941-916, Rio de Janeiro, Brazil,
[2] The University of Woverhampton, Faculty of Science and Engineering
Wulfruna St. Wolverhampton, WV1 1LY, UK City Campus - South.
E-mails:antoniotguerra@gmail.com; m.fullen@wlv.ac.uk; orofila@gmail.com; silviat.alexandre@gmail.com

Recebido em: 10/10/2013 Aprovado em: 05/12/2013
DOI: http://dx.doi.org/10.11137/2014_1_81_91

Abstract

Brazil covers 8,547,403 km^2 and is divided into five regions (Northern, North Western, Central Western, South Eastern and Southern). The diversity of climate, geology, topography, biota and human activities have contributed to the considerable diversity of soil types and thus soil erosion problems. National soils can be classified into 12 classes. These are: Oxisols (38.7%), Alfisols (20.0%), Inceptisols (2.7%), Mollisols (0.5%), Spodosols (1.6%), Gleysols (3.7%), Aridisols (2.7%), Entisols (14.5%), Vertisols (2.0%), Ultisols (1.8%), Plinthosols (6%) and Alisols (4.3%). The erodibility of these Soil Orders is reviewed and is mainly related to soil texture. Sands and loamy sands are especially erodible. Soil erosion patterns are complex, being influenced by rainfall erosivity, soil erodibility, topography, land use and management characteristics. Urban areas have specific erosion problems and there are illustrated using a case study from São Luis (north-east Brazil). Soil erosion rates can be excessive, in some cases exceeding 100 tonnes per hectare per year. Particularly serious soil erosion is associated with six regions. These are north-western Paraná State; the Central Plateau, in the Centre Western Region; Western São Paulo State; the Paraíba do Sul middle drainage basin, in Rio de Janeiro State; *Campanha Gaúcha* in Rio Grande do Sul State and *Triângulo Mineiro*, in western Minas Gerais State. Examples of effective soil conservation are presented, using case studies from both Paraná and Santa Catarina States. Integrated management of drainage basins offers a promising way forward for effective soil conservation in Brazil.
Keywords: Soil erosion; soil conservation; soil mapping

Resumo

O Brasil ocupa 8.547.403 km^2 e está dividido em cinco regiões (Norte, Nordeste, Centro-Oeste, Sudeste e Sul). A diversidade climática, geológica, topográfica, da biota e das atividades humanas tem contribuído para a grande diversidade de tipos de solo, assim como para os problemas de erosão. Solos nacionais podem ser classificados em 12 classes. Estes são**:** Latossolos (38,7%), Argissolos (20,0%), Cambissolos (2,7%), Chernossolos (0,5%), Espodossolos (1,6%), Gleissolos (3,7%), Luvissolos (2,7 %), Neossolos (14,5%), Vertissolos (2,0%), Planossolo (1,8 %), Plintossolos (6%) e Alissolos (4,3%). A erodibilidade dessas classes de solo foi revisada e relacionada principalmente à textura. Solos arenosos e franco-arenosos são especialmente mais susceptíveis à erosão. Os padrões de erosão são complexos, sendo influenciados pela erosividade da chuva, erodibilidade do solo, topografia, uso e manejo do solo. As zonas urbanas têm problemas específicos de erosão e estes são ilustrados através de um estudo de caso de São Luís (Nordeste do Brasil). As taxas de erosão são significativas, sendo em alguns casos superiores a 100 toneladas por hectare por ano. A erosão é particularmente grave associada com seis regiões: noroeste do Paraná, Planalto Central, Região Centro Oeste, Oeste do Estado de São Paulo, médio curso da Bacia do Paraíba do Sul, no Estado do Rio de Janeiro; na Campanha Gaúcha, no Rio Grande do Sul e no Triângulo Mineiro, Estado de Minas Gerais. Exemplos de conservação do solo são apresentados por meio de estudos de caso no Paraná e Santa Catarina. A gestão integrada de bacias hidrográficas oferece uma maneira promissora para a conservação do solo em vigor no Brasil.
Palavras-chave: Erosão dos Solos; Conservação dos Solos; Mapeamento Pedológico

1 Introduction

Soil erosion and land degradation is a global problem and poses a major problem in Brazil. The hazard affects both urban and rural areas within the extensive national territory (8,547,403 km^2**)** (Figure 1). In turn, these problems have serious environmental impacts and pose socio-economic problems. It is important that the soils are conserved, for the present and future generations. Although erosion is a natural phenomenon, often human activity accelerates erosion processes. Soil erosion on US agricultural soils causes the loss of an average of 30 tonnes per hectare per year (t ha^{-1} y^{-1}); some eight times quicker than rates of soil formation. A survey by Embrapa (the Brazilian Ministry of Agriculture) suggested the situation in Brazil is often worse.

According to Goudie & Boardman (2010) "*it is quite clear that the major areas of intense erosion are associated with both human and natural factors*." Boardman (2006) suggested the following countries and regions are global erosion 'hotspots:' the Loess Plateau of China, Ethiopia, Swaziland and Lesotho, the Andes, South and East Asia, the Mediterranean basin, Iceland, Madagascar, the Himalayas, the Sahel of West Africa, the Caribbean and Central America. We propose Brazil is also an erosion 'hotspot.'

Brazil is characterized by a great diversity of soil types, corresponding to a wide variety of relief forms, climates, parent materials, vegetation cover and biota. Diverse pedogenic processes thus facilitate the pedogenesis of many soil types. Related to this great diversity, Brazil has its potentialities and limitations, in terms of land use. This diversity is enhanced by regional differences in terms of settlement, land use and development.

Brazil can be divided into several regions. These include the Northern (or Amazon) Region. The Region is characterized by plains and low plateaux, a tropical climate, perennial high temperatures, high humidity, deep and highly weathered soils, high acidity and low natural fertility. These soils have low production potential, especially when they are poorly managed.

The North Western Region has diverse climates, which vary from the humid and warm, near the coast, to semi-arid (warm and dry), in the interior. There is a semi-humid transition area between these two areas. Generally, soils have medium to high natural fertility, and are usually shallow, due to the relatively low weathering rate.

The Central West Region has a vast plateau, caused by prolonged erosive processes during geological time, called the Brazilian Central Plateau. The regional characteristics include the tropical climate, with two distinct seasons: one humid and another dry (approximately six months of each one); and extensive area with deep, well drained, acid soils with low natural fertility. However, these soils have potential and can be improved with the application of lime and other organic and chemical fertilizers. Once these treatments have been carried out, the region generally has a favourable relief for mechanized agriculture.

The South Eastern Region is characterized by plateaux and mountain ranges, which reach up to 2,000 m altitude. The climate is tropical, with hot summers on the lowlands and more temperate conditions on the mountain ranges and plateaux. Soils are generally deep, well developed and have low fertility (Embrapa, 2002).

The Southern Region has many soils developed on varied parent materials, including basic rocks and varied sedimentary rocks. These produce very diverse landscapes. The climate is sub-tropical with very well defined seasons. The predominantly fertile soils have high potential for agro-pasture (Embrapa, 2002).

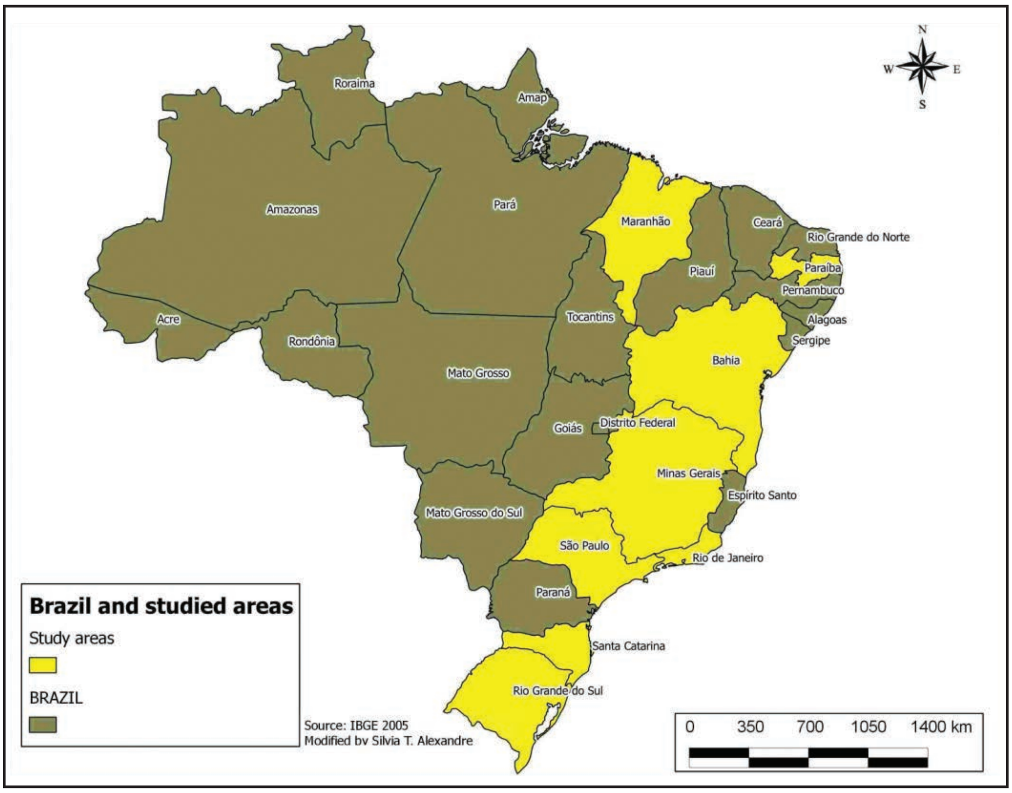
This overview of Brazilian soils, in terms of the five great Regions, is fundamental, as these regional differences play key roles for environmental differences, which affect climatic, geomorphological and pedological domains. In turn, these affect agricultural potential and soil erosion characteristics throughout Brazil.

2 Soil Types and Erosion in Brazil

The eco-environmental diversity of Brazil promotes diverse soil types, which are integral components of these ecosystems and form essential natural resources. Based on the Soil Maps of Brazil (Embrapa, 1981) and the Brazilian Soil Classification System (Embrapa, 1999) there are 12 mapped national soil classes (Figure 2).

The Great Classes can be subdivided into different types, according to the main characteristics. Soil properties and characteristics are outlined, as well as their percentage in terms of spatial cover.

Oxisols are encountered in forests (dense, open and with palm trees) and *cerrado* (a form of



Source: IBGE 2005
Modified by Silvia T. Alexandre

Figure 1 National Map of Brazil.

savannah), on relief which varies from flat to very hilly (Guerra & Botelho, 2012). They result from intense weathering of parent materials, including rocks and pre-weathered sediments. Clay fractions are usually in the latter stages of weathering (consisting of kaolinites (caulinites) and iron (Fe) and aluminum (Al) oxides). The sand fraction is dominated by minerals very resistant to weathering (Embrapa, 2002). Soil texture ranges between loamy to very clayey. Oxisols are generally deep, porous and permeable, with little difference in clay content in deep horizons. They usually possess low natural fertility. They have a high occurrence in Brazil, occupying 38.7% of national territory and are widely distributed. There are several types of Oxisols and they differ in terms of their colour, natural fertility, oxide contents and texture (Figure 2).

Alfisols characteristically have high clay content in the B horizon, but their properties are very heterogeneous. They are well structured, with variable depth and are usually coloured red to reddish yellow. Topsoils range from sandy to clayey textures and their subsoils are loamy to very clayey. In Brazil, the presence of caulinite is the main diagnostic mineralogy.

Alfisols occupy ~20.0% of Brazil and occur throughout the country. If one compares Alfisols with Oxisols, the former tend to occupy more dissected relief. They are called Bt horizon soils, due to the concentration of clay in B horizons, increased by illuviation or lateral translocation. Thus there are considerable differences in clay percentage, between A and B horizons, usually with a transition from a sandy A horizon to a clayey B horizon. This may impede water infiltration, thus decreasing profile permeability.

Inceptisols are characterized by the heterogeneity of parent materials, landscapes, and climatic conditions; therefore their properties vary considerably. The main common characteristic is the incipient evolution stage of sub-surface horizons. Often rock fragments are embedded within the soil matrix and primary non-weathered minerals are common (Embrapa, 2002). They occupy ~2.7% of Brazil, and are widespread. Individual soil units tend to be small and usually concentrated on the foot-slopes of mountain ranges. These include Serra do Mar, which stretches from south-east to south Brazil, and Serra da Mantiqueira, in the South Eastern Region (Oliveira *et al*., 1992). Inceptisols with high natural fertility are present in the North Eastern Region and Acre State (northern Brazil).

Mollisols have high soil organic matter (SOM) contents and thus have dark coloured A horizons. Typically, they have very high clay activity in the subsoil, with the presence of vermiculites and/or smectites. They are well-structured and have high base saturation. They are moderately acidic to highly alkaline and have high natural fertility (Embrapa, 2002). These soils occupy only 0.5% of Brazil and are located mainly in two areas: part of Rio Grande do Sul State (Southern Region) and part of Bahia State (North East Region).

Spodosols (usually described as Podzols in the international literature) are mainly sandy, with accumulations of SOM and Al in deep profiles. They are very poor acidic soils, having high extractable Al contents, compared with other basic ions. They cover ~1.6% of Brazil and are widely distributed, especially along the coastal plain, mainly in Bahia, Sergipe, Alagoas, Rio de Janeiro and Rio Grande do Sul States and in Western Amazonia (Embrapa, 2002).

Gleysols occupy ~3.7% of Brazil, occurring usually on low depressed areas and, therefore, they are usually wet, unless artificially drained. They normally develop under recent sediments, along the rivers and on alluvial-colluvial materials, subject to hydromorphism, in low and flat areas (Embrapa, 2002). Thus, they are widespread in Brazil, especially where the water table is very close to the soil surface during most of the year. They are poorly drained and shallow, being usually acidic with high clay contents and low silt and sand contents (Guerra & Botelho 2012). Besides occurring in all wet areas of Brazil, they are in many areas of the Amazon basin, Goiás and Tocantins States, along the River Araguaia, and along the River Paraíba do Sul in Rio de Janeiro and São Paulo States.

Aridisols are mainly in the semi-arid zones of the North Eastern Region. They occupy ~2.7% of Brazil, with high natural fertility and high capacity to retain exchangeable ions (high activity clay) and high capacity for nutrient retention in subsurface horizons, underneath the A horizon. A horizons are typically shallow, with low SOM contents and low to medium capacity to retain nutrients (Embrapa, 2002).

Ultisols typically they have sandy topsoils, contrasting with sub-surface horizons with high concentrations of clay. These subsoil horizons harden (indurate) on drying and thus they have low permeability and are poorly drained (Embrapa, 2002).

They are present in *Pantanal Matogrossense,* Mato Grosso State and Rio Grande do Sul State (Oliveira, *et al*., 1992), Amazonas, (Vieira, 1988) and Rio de Janeiro State (Silva & Mafra, 1991). They occupy 1.8% of Brazil and present visible signs of hydromorphism, due to their low permeability and because they are frequently situated on flat areas.

Entisols are poorly developed soils and occupy ~14.5% of Brazil. Their main characteristic is that they are sandy or sandy loam soils (Guerra & Botelho, 2012). They are formed mainly in sedimentary deposits and are widespread in Brazil (Embrapa, 2002). They are along many rivers developed in alluvium. They are also on mountainous areas and are very shallow (usually <50 cm deep) and are usually coarse textured, on top of rocky parent material. Entisols are found on extensive areas of São Paulo, Mato Grosso, Mato Grosso do Sul, Bahia, Pará and Maranhão States. Here the Entisols are deep (≤200 cm) and they are very well drained.

Vertisols occupy ~2.0% of Brazil (Figure 2). They are greyish to black, without significant differences in clay contents between topsoil and subsoil horizons. Nevertheless, the main characteristic is the pronounced change in moisture content, due to the presence of expansive clays, creating extensive cracks on soil surfaces in dry periods (Embrapa, 2002).

They occur mainly in the semi-arid areas of the North East, swampy areas of Mato Grosso State (called *Pantanal Matogrossense*) and in Bahia State around the State capital of Salvador, an area called *Recôncavo Bahiano*. They have high chemical fertility, but present problems in terms of their physical properties. Vertisols are poorly drained, presenting low porosity, especially in C horizons (Guerra & Botelho, 2012).

Plinthosols are encountered in very specific environmental conditions, where there is very low water flow, or frequent soil wetting (Embrapa, 2002; Guerra & Botelho, 2012). They accommodate soils that contain plinthite (an iron-rich humus-deficient mixture of kaolinitic clay with quartz and other constituents). They are known as groundwater laterite soils (*lateritas hidromórficas*) in Brazil. They cover ~6.0% of Brazil and are widespread, especially in lowlands, gently sloping areas, alluvial areas, depressions, river terraces and along some river banks. Therefore, these soils are very common in the Amazon basin, *Marajó* Island, Amapá, Maranhão, Tocantins and Goiás States and *Pantanal*

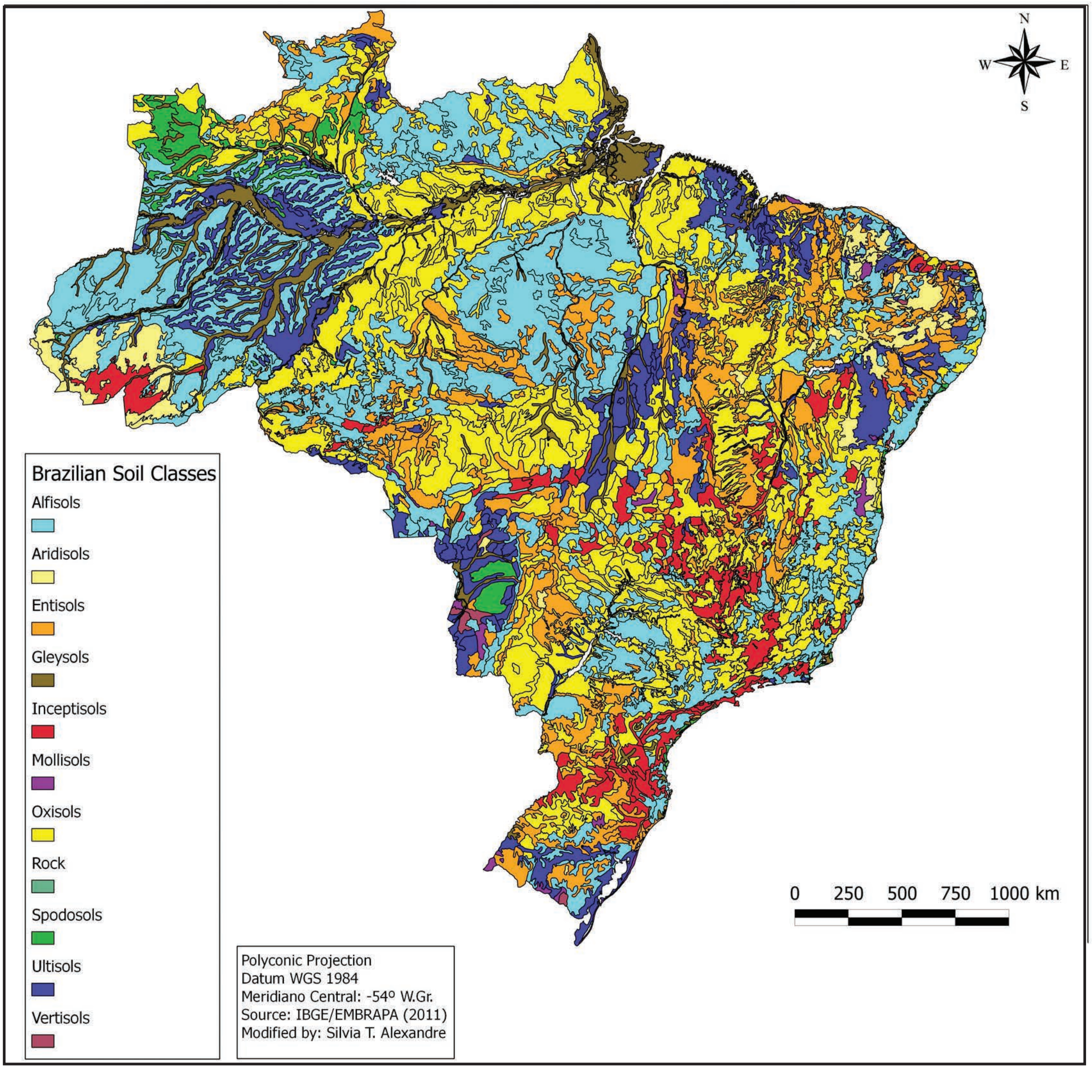


Figure 2
Soil Map of Brazil
(Based on US
Taxonomy).

Matogrossense (Mato Grosso State). All these soils are situated on low-lying flat lands. They are mainly acidic and have low nutrient reserves (Embrapa, 2002).

Alisols are poorly drained soils with a dense subsurface clay layer, which causes relatively high concentrations of Al ions in the rhizosphere. They cover 4.3% of Brazil and have low natural fertility (Embrapa, 2002). These soils are acidic and in some there is a significant increase in clay content in deeper horizons. They are distributed in sub-tropical Brazil: Paraná, Santa Catarina and Rio Grande do Sul States, but they also occur in tropical environments in western parts of the Amazon basin.

Histosols (organic soils) occur in Brazil, but they are in relatively small, widely distributed areas. Thus, scale issues preclude their inclusion on the National Soil National Map. Histosols are present on some mountain ranges at ≥800 m altitude. Lowland Histosols are present within some drainage basins, including the Amazon, São Francisco and Paraíba do Sul basins. Depth of organic material is ≤80 cm, they have very low bulk densities (usually <0.8 g/cm^3) and they are poorly drained, due to the water retentive properties of the organic matter. The rest (1.5%) of national territory is covered either by water or rock outcrops.

2.1 Soil Erosion and its Impacts

Although there are several agents of erosion, water is the most important one. Cultivation can promote soil erosion, due to ploughing and harvesting, which moves soil down slopes. These erosion processes occur in Brazil, with water being the main erosive agent, causing serious problems, both where the processes occur (on-site) and off-site.

Off-site affects include river and reservoir siltation and water pollution. For instance, the total amount of sediment deposited into Itaipu reservoir was estimated at ~12.5 million tonnes by 1982 (Derpsch *et al.,* 1991). Scientists are trying to predict these geomorphological processes, in order to avoid or minimize negative environmental impacts. These include losses of both natural resources and finances, due to the costs of decreased soil productivity and the funds which need to be invested by local authorities and farmers to clear sediments and prevent erosion. Hufschmidt & Glade (2010) stressed the importance of adopting engineering measures to conserve soils.

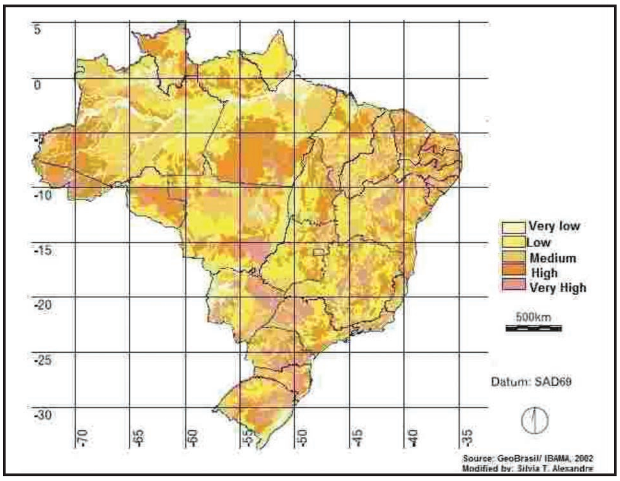
Soil erosion rates have been investigated in different parts of the world and data from USDA (1994) has estimated a global mean of 14 t ha^{-1} year^{-1}, with 9-11 t ha^{-1} year^{-1} being considered unacceptably high. Soil erosion rates in Brazil are highly variable and depend on several factors. These include soil types and their associated properties, the rainfall regime, with generally higher erosivity during summer, frequent low vegetation cover, long steep slopes with convergent flows and land mismanagement. The importance of land mismanagement has been particularly emphasized in Brazil (Guerra & Botelho, 2012).

In places erosion rates exceed 20 t ha^{-1} y^{-1} (Embrapa, 2002). For instance, erosion was estimated to average ~40 t ha^{-1} y^{-1} over 6 million hectares of cultivated land in Rio Grande do Sul State (Schmidt *et al.,* 1989). In Paraná State, the average was 15-20 t ha^{-1} y^{-1} on agricultural fields under intense mechanization (Paraná, 1994). Figure 3 shows the susceptibility of soils to water erosion, where susceptibility is classed as:

- Very low (there is very little risk of water erosion).
- Low (there is minimal risk of water erosion).
- Medium (there is some risk of water erosion, but depending on soil properties, rainfall erosivity and land use and management, this risk may be increased).
- High (depending on soil classes, rainfall erosivity, and land use and management, there is a high probability of excessive water erosion).
- Very high (there is a very high probability of very excessive water erosion). Thus, on these soils, there should be no forest clearance or arable soil use. These areas are very sensitive to soil erosion and they should be maintained as Conservation Units. According to Brazilian Legislation, Conservation Units are protected areas. In some, no economic activity is permitted, whereas in others some economic activity is permitted, but only with official government permission.

In São Pedro drainage basin, Macaé Municipality, Rio de Janeiro State, erosion was estimated at 102 t ha^{-1} year^{-1}, on sandy loam Oxisol and Inceptisol pasture soils, largely due to gully erosion (Loureiro, 2013). This is a rainy area, with an average annual precipitation of ~1,800 mm, concentrated during summer months (December-March). Soil erosion assessment in this area shows the role of land use and management in provoking accelerated erosion, especially gully erosion over recent decades (Figure 4).

In São Luís City (Maranhão State), North Eastern Region, urban gully erosion is severe. Erosion has been monitored using periodic surveys of gully morphology.



Source: GeoBrasil/ IBAMA, 2002
Modified by: Silvia T. Alexandre

Figure 3 Simplified soil erosion by water map of Brazil.

Between 2000-2008, in Sacavém District, gully retreat totalled 4 m, equivalent to mean of 0.5 m per year (Guerra *et al.,* 2010). São Luís, like many other Brazilian cities, has experienced rapid population growth in recent decades, which has created a series of socio-economic and environmental problems, including accelerated soil erosion. Sacavém is one of these communities where natural and human factors contribute to severe gully erosion. Rapid population and urban growth has intensified problems, compounded by poor planning and improper soil use (Figure 5).

Developments at the Sacavém gully can be monitored on the LAGESOLOS (Laboratory for Environmental Geomorphology and Soils Degradation of the Federal University of Rio de Janeiro) web site(Figure 6).

In Paraíba State (North Eastern Brazil), in the small (5.73 km^2) experimental drainage basin of the Guaraíra River, between Alhandra and Pedras de Fogo Municipalities, taking into account two different years (1974 and 2011), erosion rates were >20 t ha^{-1} y^{-1}. Particularly high erosion rates were found on bare soils and sugar cane plantations. Land use and management played a critical role in causing such high soil erosion rates (Costa & Silva, 2012).

Generally, the highest soil erosion rates in Brazil occur where vegetation has been cleared without conservation measures. This is the case of the Campinas River Catchment, in Joinville Municipality, Santa Catarina State, Southern Brazil. Some 93% of the study area lost 1-3 t ha^{-1} y^{-1} of soil from areas under native forests and agriculture with effective conservation measures (Guimarães *et al.,* 2011). Nevertheless, very high soil losses were measured and were associated with rural roads and urbanized areas with bare soil. On steep (10-35^{o}) slopes, rates can exceed 200 t ha^{-1} y^{-1} (Guimarães *et al.,* 2011).

Intense soil erosion also occurs in Bahia State (North Eastern Region), in the Colonia River Catchment, in Itapetinga Municipality. Soil loss was estimated to be a mean of 47 t ha^{-1} y^{-1} for the 27 years between 1975-2002 (Silva *et al.,* 2011). Measurements of soil loss from forests and protected areas within the same catchment show total losses were 9-20 t ha^{-1} y^{-1}.

Although there are many areas in Brazil where soil erosion occurs, six regions merit particular discussion (Guerra & Botelho, 2012). The first one is north-western Paraná State on Oxisols and Alfisols, where accelerated erosion started in 1950. This was due to several factors, including vegetation clearance, followed by disorganized urban growth and soil mismanagement on coffee, cotton and maize plantations and on cattle rangelands. These developments degraded soils in several municipalities of this region.

The second one is the Central Plateau, in the Centre Western Region, as well as some parts of the South Western Region, mainly on Oxisols, Alfisols, Entisols and Inceptisols. The gentle topography of those areas facilitate mechanized agriculture, which increases soil compaction (i.e. increased soil bulk density) and thus provokes runoff and high soil erosion rates. The rainy season, concentrated in less than six months, with an average ~1,500 mm of rain, is another contributory factor.

Figure 4 Gully erosion in São Pedro drainage basin, Macaé Municipality, Rio de Janeiro State in April 2011 (Photo by Maria do Carmo Oliveira Jorge).

The third area is Western São Paulo State, which corresponds to 40% of State territory. The main soil classes are Oxisols and Alfisols with sandy loam textures. There are many gullies in the area, some of them >1 km long, ≤50 m wide and ≤30 m deep. The intense soil erosion causes problems for agriculture, because of the loss of soil fertility, but also due to off-site effects, especially siltation in rivers and reservoirs. Once more, land use and soil mismanagement are the main reasons for land degradation in this region.

Figure 5 Land rehabilitation in gullied area in São Luís City. Photo by José Fernando Rodrigues Bezerra.

Figure 6 Gullied area in São Luis Municipality, Maranhão State, during rehabilitation work .Photo by Jose Fernando Rodrigues Bezerra.

The fourth area is the Paraíba do Sul middle drainage basin, in Rio de Janeiro State, mainly on Oxisols, Alfisols, Entisols and Inceptisols, all of them with sandy loam textures. Vegetation clearance since the mid-18th century was critical in initiating erosion. Vegetation was cleared for coffee plantations and was followed by extensive cattle ranching, which caused land degradation and fertility loss on these soils (Guerra & Botelho, 2012). The concentrated erosive summer rainfall regime accelerated erosion.

The fifth region is *Campanha Gaúcha* in Rio Grande do Sul State, including the municipalities Alegrete, São Francisco de Assis, Santana do Livramento, Itaqui and Manuel Viana. The soils are erodible sandy or sandy loam Alfisols or Oxisols and experience an erosive rainfall regime. Soya-bean plantations and cattle ranching, both without conservation measures, are the main factors explaining land degradation. Wind erosion is also a local problem.

The sixth area is *Triângulo Mineiro*, in western Minas Gerais State. This includes the municipalities Uberlândia, Uberaba and Araguari. The main soil types are erodible sands and sandy loam Oxisols, Alfisols and Inceptisols. Accelerated erosion processes were initiated by vegetation clearance for cattle ranching. The concentrated erosive rainfall regime is another factor which explains widespread gully erosion in the region.

Figure 3 shows five classes of susceptibility to water erosion, ranging from very low to very high. Most of the very low and low classes are in Amazonia, where slope angles are gentle. Although there has been forest clearance in recent decades, this is remains the most vegetated region in Brazil. The medium class is present in different parts of Brazil and this is due to a combination of factors (soil properties, land use and cover, rainfall regime and slope characteristics).Most of the high and very high classes are concentrated in Southern and South East Brazil, where there is the highest pressure on land use, due to intensive agriculture practises, often without conservation measures.

Some of the soils are very erodible and experience intense erosive summer rainfall (December-March). High and very high soil erosion classes are present in Amazonia, due to forest clearing and intensive soil use, mainly for soya-bean crops often without soil conservation practises.

It is very difficult to accurately estimate total soil erosion for such a large country as Brazil. The Handbook of Sustainable Consumption (Consumo Sustentável, 2005) estimated the overall national loss of soil due to soil erosion to be 822-1000 million tonnes per year.

Given the large size (area 8,547,403 km^2) and population (190 million in the 2010 Census) of Brazil, it is difficult to accurately assess the magnitude and costs associated with soil erosion. Best estimates are that the average rate of soil erosion is ~15.4 t ha^{-1} y^{-1} (Embrapa, 2002). This compares with a maximum tolerable rate of soil erosion (i.e. a rate which will not seriously impair soil fertility) of ~2 t ha^{-1} y^{-1}. Similarly, estimates of total costs of damage caused by soil erosion are difficult to assess. This problem is compounded by the diversity of associated costs and difficulties in accurately assessing costs. Expenditure includes costs to replace lost nutrients, costs to repair sediment damage to water resources, damage to rural roads and other infrastructure and associated fuel and electricity costs. National costs are estimated at USD 5 billion per year, while average costs of soil erosion for farmers is estimated at USD 22 per hectare per year (Embrapa, 2002).

3 Soil Conservation

In order to rationalize land use and management in Brazil, drainage basin management projects have been in progress since 1980. The drainage basin can be considered a natural planning unit,where the integrative and dynamic action of land uses can be systematically analysed, and where each component may interact with other parts of the system (Bertoni & Lombardi Neto, 1990).

Paraná State was a pioneer in terms of projects on micro-drainage basin productivity management. This was because of intense land degradation in the State during the 1980s. This was especially problematic in the north-west of Paraná State, due to intensive agricultural activities (Guerra & Botelho, 2012). Some 15 years after this project started, over 2,148 micro-drainage basins are managed by the project, encompassing 365 municipalities and covering 6.2 million hectares, some 45% of the agricultural area of the State. The results can be measured by increased crop production and productivity, and decreased costs, in terms of decreased use of fertilizers, the maintenance of rural roads and water treatment.

In Santa Catarina State, a micro-drainage basin project was implemented from 1991-1997, using funding from the World Bank. The project helped 81,000 farmers, in 520 micro-drainage basins, and benefited 25% of the State's agricultural areas. Other States, including São Paulo, Mato Grosso do Sul and Rio de Janeiro, have already started micro-drainage projects. However, to date, their actions have targeted very few micro-drainage basins (Guerra & Botelho, 2012).

Micro-drainage basin project strategies can be summarized in three main basic characteristics: 1. to increase soil vegetation cover duration and extent; 2. to improve soil structure and drainage, and 3. to control soil surface flow, (Bragagnolo, 1994). The increase in vegetation cover protects soil against splash erosion, induces better soil structure due to increased SOM content, reduces runoff and increases infiltration.

Examples of effective soil conservation practises in Brazil include:

1 Increased extent and density of vegetal cover.

2 Use of green manure (i.e. the addition and incorporation of non-decomposed vegetal biomass on fallow soils).

3 Good soil management practises, particularly minimum tillage.

4 Maintaining cover on soils, especially retaining harvest residues on topsoils, thus adding organic matter to soil systems.

5 Improved cattle management systems and optimizing the combination of these systems with arable cropping systems to minimize soil erosion.

6 Re-afforestation and particular protection of riparian vegetation and erodible soils.

7 Contour cultivation. Experiments in Brazil have shown this can reduce runoff by ≤30% and soil loss by ≤50% (Bertoni & Lombardi Neto, 1990).

8 Vegetative buffers (strips of vegetation) in agricultural areas. These act as physical barriers to runoff and erosion and encourage the infiltration of water.

9 Strips of stones, where stones in agricultural areas are placed in small channels dug parallel to contour lines to reduce water surface flow.

10 Construction of small retention basins in small depressions, between areas of permanent agriculture.

11 Construction and maintenance of vegetation barriers to act as 'windbreaks' and thus decrease wind erosivity in areas subject to wind erosion.

All these conservation practises have promoted much more sustainable agriculture in Brazil, which improves soil drainage and simultaneously reduces soil erosion. Nevertheless, in many areas, soil degradation still occurs, due to the use of conventional agricultural systems and cattle ranching.

Experimental stations and modelling play important roles in assessing soil loss and runoff in Brazil. For instance, SWAT (Soil and Water Assessment Tool) has been used to develop conservation practises to reduce runoff, soil loss and nutrient losses in São Bartolomeu drainage basin, Viçosa Municipality, in Minas Gerais State (Rocha *et al.,* 2012). The model allowed the identification of critical areas in terms of runoff generation, sediment yield and nutrient loss. Conservation practises were simulated to reduce the impact of these processes. The simulated results showed a mean annual runoff (R) of 35 mm, mean annual sediment yield (SY) of 51 t ha^{-1} y^{-1}, 3.6 t ha^{-1} y^{-1} loss of total nitrogen (TN) and 1.6 t ha^{-1} $year^{-1}$ loss of total phosphorus (TP). After taking into account conservation practices, the results showed an increase in water infiltration, reducing R, SY, TN and TP by 18, 66, 25 and 30%, respectively (Rocha *et al.,* 2012).

The advance in techniques which apply geoprocessing and Geographical Information Systems (GIS), together with erosion monitoring and modelling, have increased our knowledge on soil erosion and soil conservation. These techniques encompass mapping soil types and soil potential use and other types of maps, field and laboratory work, the adoption of rational soil use and soil management strategies and micro-drainage basin management. These techniques are of considerable applied value, both to farmers, who deal directly with soils, and to State governments, who invest in soil conservation. The Federal Government also invests in soil conservation through several national agencies, especially Embrapa.

4 Conclusions

Soil erosion is the product of complex interactions between rainfall regime, soil properties, slope characteristics, vegetation cover and land use and management. Their interaction often produces excessive erosion rates in Brazil. Understanding soil erosion as a geomorphological process is an essential step towards developing effective soil conservation strategies. There is a close association between soil classes in Brazil and soil erodibility and field measurements suggest erosion rates often far exceed tolerable levels and thus impair the ability of soil systems to sustainable produce crops.

Quantitative data on measured soil erosion rates are sparse in Brazil. However, the few available studies show total soil loss often exceeds 50 t ha^{-1} y^{-1} and can exceed 100 t ha^{-1} y^{-1}. Thus, Brazil is one of the global erosion 'hotspots.' Due to the very diverse environmental conditions, land use and management, it is very difficult to produce reliable average estimates of soil loss for the whole country. It is suggested a useful step would be to produce soil erosion estimates for the five regions of Brazil. This will require an integrated programme of surveys, monitoring and modelling to be conducted by Universities and Research Centres throughout Brazil. Such data would inform the viability of soil conservation practises. Integrated management of drainage basins offers a promising way forward for effective soil conservation in Brazil.

5 Acknowledgements

The authors thank CNPq and FAPERJ for the financial support.

6 References

Bertoni, J. & Lombardi Neto, F. 1990. *Conservavação dos Solos*. São Paulo, Icone. 355p

Boardman, J. 2006. Soil erosion science: reflections on the limitations of current approaches. *Catena, 68***:** 73-86.

Bragagnolo, N. 1994. Uso dos solos altamente suscetíveis à erosão. *In*: PEREIRA, V.P.; FERREIRA, M.E. & CRUZ, M.C.P. (eds.). *Solos altamente suscetíveis à erosão*. Editora Sociedade Brasileira de Ciência do Solo, p 3-16.

Consumo Sustentável. 2005. *Manual de Educação*. Brasília, Consumers International/MMA/MEC/IDEC.160 p.

Costa, S.G.F. & Silva, R.M. 2012. Potencial natural e antrópico de erosão na bacia experimental do riacho Guaraíra. Cadernos dos Logepa, *7*(1): 72-91.

Derpsch, C.H.; Roth, C.H.; Sidiras, N. & Kopke, U. 1991. Controle da erosão do Paraná, Brasil: *sistemas de cobertura do solo, plantio direto e prepare conservacionista do solo*. Eschborn: Deutsche Gesellschaft fur Technische Zusammenarbeit (GTZ); IAPAR, Londrina, Brazil, p. 272.

EMBRAPA. 1981. Mapa de Solos do Brasil, escala 1:5.000.000. Serviço Nacional de Levantamento e Conservação de Solos. Rio de Janeiro, Brasil, Centro Nacional de Pesquisa em Solos. Sistema brasileiro de classificação de solos, p. 185.

EMBRAPA. 1999. Produção de Informação. Brasília, Brazil. 412 p.

EMBRAPA. 2002. *Uso agrícola dos solos brasileiros*. Embrapa Solos, Rio de Janeiro, Brazil. 174 p.

Goudie, A.S. & Boardman. J. 2010. Soil Erosion. *In*: ALCÁNTARA-AYALA, I. & GOUDIE, A.S. (eds.). *Geomorphological Hazards and Disaster Prevention*. Cambridge University Press, p. 177-188.

Guerra, A.J.T.; Bezerra, J.F.R.; Lima, F.S.; Mendonça, J.K.S.; Guerra, T.T.; Bühmann, C.; Paterson, D.G.; Pienaar, G.; Nell, J.P.; Mulibana, N.E.; van Deventer, P.W. & Fullen, M.A. 2010. Land rehabilitation with the use of biological geotextiles in two different countries. *Sociedade & Natureza*, *22*(3): 431-446.

Guerra, A.J.T. & Botelho, R.G.M. 2012. Erosão dos solos. *In*: CUNHA, S.B & GUERRA, A.J.T. (eds.). *Geomorfologia do Brasil*. 8th edition, Bertrand Brasil, p. 181-227.

Guimarães, R.Z.; Lignau, C.; Rizzi, N.R.; Schechi, R.G. & Bianchi, R.C. 2011. *Espacialização da perda de solo por erosão laminar na micro-bacia do rio Campinas,* Joinville, Santa Catarina. *Ra´E Ga*, *23*: 32-64.

Hufschmidt, G. & Glade, T. 2010. Vulnerability analysis in geomorphic risk assessment. *In*: ALCÁNTARA-AYALA, I. & GOUDIE, A.S. (eds.). *Geomorphological Hazards and Disaster Prevention*. Cambridge University Press, UK, p. 233-243.

LAGESOLOS (Laboratory for Environmental Geomorphology and Soils Degradation of the Federal University of Rio de Janeiro), www.lagesolos.ufrj.br (accessed on 17/09/2013).

Loureiro, H. 2013. *Monitoramento e diagnóstico de áreas degradadas na bacia hidrográfica do rio São Pedro (RJ) – Estudos experimentais em voçoroca e utilização de geotêxteis de fibra de bananeira*. Programa de Pós-graduação em Geografia, Universidade Federal do Rio de Janeiro, Dissertação de Mestrado, 195p.

Oliveira, J.B.; Jacomine, P.K.T. & Camargo, M.N. 1992. *Classes gerais de solos do Brasil*. 2ª ed., Jaboticabal, São Paulo, FUNEP, 201 p.

Paraná. 1994. *Manual técnico do subprograma de manejo e* *conservação do solo*. Secretaria de Estado de Agricultura e do Abastecimento. Curitiba, 306p.

Rocha, E.O.; Calijuri, M.L.; Santiago, A.F.; Assis, L.C. & Alves, L.G.S. 2012. The contribution of conservation practices in reducing runoff, soil loss and transport of nutrients at the watershed level. *Water Resources Management. JCR, 26*: 3831-3852.

Schmidt, A.V. 1989. Terraceamento na região Sul. *In*: SIMPÓSIO SOBRE TERRACEAMENTO AGRÍCOLA, *Proceedings*, Fundação Cargill, p. 23-25.

Silva, A.S. & Mafra, N.M.C. 1991. Considerações a respeito da erosão em terraços do rio Itabapoana (Rio de Janeiro State). *In*: BRAZILIAN CONFERENCE ON SOIL SCIENCE. *Book of Abstracts*, Porto Alegre, Rio Grande do Sul State,139 p.

Silva, V.A.; Moreau, M.S.; Moreau, A.M.S. & Rego, N.A.C. 2011. Uso da terra e perda de solo na bacia hidrográfica do Rio Colônia, Bahia. *Revista Brasileira de Engenharia Agrícola Ambiental*, *15(3)*: 310-315.

USDA. 1994. *National Resources Inventory*. United States Department of Agriculture, Conservation Service, Washington, USA.

Vieira, L.S.1988. *Manual de Ciência do Solo, com ênfase aos solos tropicais*. Agronômica Ceres, São Paulo, São Paulo State, 464p.

The New York Times Reprints

January 16, 2011

After Deadly Mudslides in Brazil, Concern Turns to Preparedness

By **ALEXEI BARRIONUEVO**

SÃO PAULO, Brazil — Unrelenting rains for much of the weekend complicated the search for scores of people still missing after violent floods stirred mudslides that ripped through hillside communities around Rio de Janeiro, killing more than 600 people since last week.

The hardest hit towns — Petrópolis, Teresópolis and Nova Friburgo — have been scenes of widespread devastation since last week. Residents walked dazed through the mud, searching for missing family members and what remains of their belongings. Communications, electricity and potable water were still lacking in several areas, leaving disaster experts to lament Brazil’s lack of preparedness for deadly rains, which they say are becoming more common.

The death toll climbed to 617 early Sunday, with nearly 14,000 reported homeless or having abandoned their homes, according to Rio de Janeiro State officials.

“We still haven’t found anyone,” said Adalberto Mota, 52, a store clerk who walked through a river of mud searching for five family members in the Vale do Cuiabá neighborhood of Petrópolis.

“I just want to leave,” he said. “This was a lovely area, a touristic spot, but it is impossible to live here now.”

The tragedy around Rio was Brazil’s deadliest natural disaster. For much of its history, Brazil has been blessed like almost no other country of its size to be almost free of such calamities. Earthquakes, tornadoes, hurricanes, blizzards, erupting volcanoes — none have proved threats to Brazil.

Until recently, the most costly and best-known disasters were severe droughts, said Margareta Wahlstrom, the assistant secretary general for the United Nations’ International Strategy for Disaster Reduction.

“But in the last few years the increasing frequency of floods, high winds and storms has become part of the new normal of Brazil,” she said. “The political choice we have today is to not treat disasters as events that come and go, but decide that you plan for them and realize that they are very costly.”

Brazil has experienced 37 disastrous floods since 2000, said Debarati Guha Sapir, a professor at the Catholic University of Louvain in Brussels who heads a World Health Organization collaborating center on disasters. Seven occurred in 2009 and four in 2008. The rain-related disasters have affected nearly five million people over the last two decades, she said.

More than 280 people died in Rio State in flooding and landslides last year, and at least 75 more in São Paulo State. That followed the more than 130 who died during heavy rains in Santa Catarina State in 2008.

But disaster experts say that the stark difference in the death tolls in Brazil and Australia, where at least 28 people have died in flooding in the northeast in the past two weeks, reveal a wide gap in the preparedness of the countries and their flood management policies.

“In a country like Brazil, which is not a poor country, where technological expertise and resources are really not a problem, large numbers of people dying from floods is not a good sign,” Dr. Sapir said. What Brazil lacks, she said, are “the political will and the priority that public authorities must give to the issue of flood management.”

The hillside areas around Rio lacked early warning systems or effective community organizations that might have helped residents to wake one another as the rains intensified last Tuesday night, disaster experts and residents said. Most people are believed to have died early Wednesday morning as they slept, when water-loosened earth swept their houses away.

Australia had not experienced severe floods since the early 1970s, Ms. Wahlstrom said, but annual cyclones and minor floods led officials to develop early-warning systems and evacuation guides that residents were regularly drilled on. Better drainage infrastructure and better quality housing also helped, she said.

Rio de Janeiro State officials have cited irregular occupation of areas at risk of floods and landslides as the main reason that so many have been dying. Carlos Minc, Rio’s environment secretary, said Thursday that the state’s civil defense authority urgently needed to relocate residents in high-risk areas. “The next rain will destroy everything that still remains,” he said. “We do not have time for contemplation.”

The city of Rio, in geological mappings, has identified 177 regions with areas at risk to rain-related events.

City officials have been training community leaders to assist the civil defense authorities during heavy rains, arming them with cellphones that would receive messages alerting them, so they could warn neighbors to evacuate.

In the case of the devastated hillside communities, which are more than 30 miles from the city of Rio, the National Institute of Meteorology forecast severe rains in the area before disaster struck. But without an integrated warning system in the state of Rio to warn local mayors, residents were not evacuated before the rains came.

Last year Brazil established a national emergency management system and it is working on an integrated system that would strengthen disaster management in all states.

In Rio State, officials have already tried to relocate some groups out of high-risk areas. But the results have been mixed.

After last year's deadly landslides in the Morro do Bumba slum in Niterói, across Guanabara Bay from the city of Rio de Janeiro, officials relocated residents to apartments far from the slum. The residents have since complained that they are paying higher transportation costs, have had to move their children to new schools and lost contact with friends and family members.

United Nations officials spoke with Brazilian officials last year after the Niterói disaster, in which more than 160 people died, about the complexity of moving people to safer areas and criticized the Niterói relocation efforts.

"There was no public transport, there were no jobs, no social infrastructure," Ms. Wahlstrom said. "Experience anywhere in the world shows that just moving people is not working."

But in some neighborhoods of the hillside towns, where residents are still digging out of the mud, the options are limited.

"Some houses can be rebuilt, but the great majority will have to be demolished and the area will have to be reforested," Luiz Eduardo Peixoto, president of the Emergency Action Committee in Petrópolis, said on Saturday. "This accident changed the course of the river. It changed the geography."

And it has changed attitudes. At a school in the center of Itaipava, a neighborhood in Petrópolis, dozens of residents with nowhere to go could only sit and wait on Saturday for donations to arrive.

Diana Viana said she managed to escape the devastation with her 2-year-old son, brother and mother. But her house was swept away.

"I don't want to even think about continuing to live here. It's very dangerous," Ms. Viana said, her eyes filled with tears. "I don't want to risk my life, the life of my child.

“I never thought that this could happen.”

Roberta Nápolis contributed reporting from Petrópolis, Brazil.

LAND DEGRADATION & DEVELOPMENT

Land Degrad. Develop. **15**: 499–512 (2004)

MAPPING SOIL EROSION RISK IN RONDÔNIA, BRAZILIAN AMAZONIA: USING RUSLE, REMOTE SENSING AND GIS

D. LU,[1]* G. LI,[2] G. S. VALLADARES[3] AND M. BATISTELLA[3]

[1] *Center for the Study of Institutions, Population, and Environmental Change (CIPEC) Indiana University, Bloomington, IN, USA*
[2] *Department of Geography, Geology, and Anthropology, Indiana State University, Terre Haute, IN, USA*
[3] *Brazilian Agricultural Research Corporation, Embrapa Satellite Monitoring, Campinas, São Paulo, Brazil*

Received 28 October 2003; Revised 22 March 2004; Accepted 1 April 2004

ABSTRACT

This article discusses research in which the authors applied the Revised Universal Soil Loss Equation (RUSLE), remote sensing, and geographical information system (GIS) to the maping of soil erosion risk in Brazilian Amazonia. Soil map and soil survey data were used to develop the soil erodibility factor (K), and a digital elevation model image was used to generate the topographic factor (LS). The cover-management factor (C) was developed based on vegetation, shade, and soil fraction images derived from spectral mixture analysis of a Landsat Enhanced Thematic Mapper Plus image. Assuming the same climatic conditions and no support practice in the study area, the rainfall–runoff erosivity (R) and the support practice (P) factors were not used. The majority of the study area has K values of less than 0·2, LS values of less than 2·5, and C values of less than 0·25. A soil erosion risk map with five classes (very low, low, medium, medium-high, and high) was produced based on the simplified RUSLE within the GIS environment, and was linked to land use and land cover (LULC) image to explore relationships between soil erosion risk and LULC distribution. The results indicate that most successional and mature forests are in very low and low erosion risk areas, while agroforestry and pasture are usually associated with medium to high risk areas. This research implies that remote sensing and GIS provide promising tools for evaluating and mapping soil erosion risk in Amazonia. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: soil erosion risk; RUSLE; remote sensing; GIS; Brazilian Amazonia

INTRODUCTION

The adverse influences of widespread soil erosion on soil degradation, agricultural production, water quality, hydrological systems, and environments, have long been recognized as severe problems for human sustainability (Lal, 1998). However, estimation of soil erosion loss is often difficult due to the complex interplay of many factors, such as climate, land cover, soil, topography, and human activities. In addition to the biophysical parameters, social, economic, and political components also influence soil erosion (Ananda and Herath, 2003). Accurate and timely estimation of soil erosion loss or evaluation of soil erosion risk has become an urgent task.

Scientists have been involved in soil erosion research for a long time, and many models for soil erosion loss estimation have been developed (Wischmeier and Smith, 1978; Nearing *et al.*, 1989; Adinarayana *et al.*, 1999; D'Ambrosio *et al.*, 2001; Veihe *et al.*, 2001; Shen *et al.*, 2003). Fullen (2003) summarized some keynote papers about soil erosion in northern Europe, and Lal (2001) highlighted major empirical models for predicting soil erosion loss. In practice, the Universal Soil Loss Equation (USLE) and later the Revised Universal Soil Loss

---

*Correspondence to: D. Lu, CIPEC—Indiana University, 408 N. Indiana Avenue, Bloomington, IN 47408, USA. E-mail: dlu@indiana.edu

Contract/grant sponsor: National Science Foundation, USA; contract/grant numbers: 95-21918 and 99-06826.
Contract/grant sponsor: National Aeronautics and Space Administration, USA; contract/grant number: N005-334.
Contract/grant sponsor: Embrapa Satellite Monitoring, Brazil.

Equation (RUSLE) has been the most widely used model in predicting soil erosion loss. The USLE was originally developed for soil erosion estimation in croplands on gently sloping topography (Wischmeier and Smith, 1978). The RUSLE has broadened its application to different situations, including forest, rangeland, and disturbed areas (Renard *et al.*, 1997). Traditionally, these models were used for local conservation planning at an individual property level. The factors used in these models were usually estimated or calculated from field measurements. The methods of quantifying soil loss based on erosion plots possess many limitations in terms of cost, representativeness, and reliability of the resulting data. They cannot provide spatial distribution of soil erosion loss due to the constraint of limited samples in complex environments. So, mapping soil erosion in large areas is often very difficult using these traditional methods.

The use of remote sensing and geographical information system (GIS) techniques makes soil erosion estimation and its spatial distribution feasible with reasonable costs and better accuracy in larger areas (Millward and Mersey, 1999; Wang *et al.*, 2003). For example, a combination of remote sensing, GIS, and RUSLE provides the potential to estimate soil erosion loss on a cell-by-cell basis (Millward and Mersey, 1999). Boggs *et al.* (2001) assessed soil erosion risk based on a simplified version of RUSLE using digital elevation model (DEM) data and land-units maps. Bartsch *et al.* (2002) used GIS techniques to interpolate RUSLE parameters for sample plots to determine the soil erosion risk at Camp Wiliams, Utah. Wilson and Lorang (2000) reviewed the applications of GIS in estimating soil erosion, discussed the difficulty and limitations of previous research and identified that GIS provided tremendous potential for improving soil erosion estimation. Wang *et al.* (2003) used a sample ground dataset, Thematic Mapper (TM) images, and DEM data to predict soil erosion loss through geostatistical methods (i.e., collocated cokriging and a joint sequential cosimulation model). They showed that such methods provided significantly better results than using traditional methods. In general, remote-sensing data were primarily used to develop the cover-management factor image through land-cover classifications (Millward and Mersey, 1999; Reusing *et al.*, 2000; Ma *et al.*, 2003), while GIS tools were used for derivation of the topographic factor from DEM data, data interpolation of sample plots, and calculation of soil erosion loss (Cerri *et al.*, 2001; Bartsch *et al.*, 2002; Wang *et al.*, 2003).

In many situations, land managers and policy makers are more interested in the spatial distribution of soil erosion risk than in absolute values of soil erosion loss. Different approaches have been used to assess the soil erosion risk, including empirical erosion models (Boggs *et al.*, 2001; Cerri *et al.*, 2001; Bartsch *et al.*, 2002), a ranking method based on selected indicators such as percentage of bare ground, aggregate stability, organic carbon, percentage clay, and bulk density (Shakesby *et al.*, 2002), and qualitative erosion risk mapping based on the combination of five factors (geology, soil, relief, climate, and vegetation) (Vrieling *et al.*, 2002).

Brazilian Amazonia has experienced high deforestation rates since the 1970s, with large areas of mature forest being converted to patches of different successional stages, agricultural lands, and pastures (Batistella *et al.*, 2003). The deforestation has been recognized as a major cause of soil degradation through soil erosion and the changes in important climate and ecosystem components (Thiam, 2003). However, the evaluation of soil erosion risk within Brazilian Amazonia has not attracted sufficient scientific attention. This article explores this topic using a simplified RUSLE based on the integration of remote sensing and GIS in the moist tropical region of the Brazilian Amazonia and examines the relationships between land use and land cover (LULC), and soil erosion risks.

BRIEF DESCRIPTION OF THE RUSLE

The RUSLE represents how climate, soil, topography, and land use affect rill and interrill soil erosion caused by raindrop impact and surface runoff (Renard *et al.*, 1997). It has been extensively used to estimate soil erosion loss, to assess soil erosion risk, and to guide development and conservation plans in order to control erosion under different land-cover conditions, such as croplands, rangelands, and disturbed forest lands (Millward and Mersey, 1999; Boggs *et al.*, 2001; Mati and Veihe, 2001; Angima *et al.*, 2003). The RUSLE is expressed as:

$$A = R\ K\ LS\ C\ P, \tag{1}$$

Table I. Summary of main methods for developing RUSLE parameters

	Methods	References
R	Using erosion index values for all rainfall storms in one year	Wischmeier and Smith, 1978
	Using average monthly precipitation and average annual precipitation	Renard and Fremund, 1994
	Using a regression model based on measured annual precipitation	Millward and Mersey, 1999
	Using a regression model of the *R* factor with average annual precipitation and elevation data	Mikhailova *et al.*, 1997
	Using geostatistical methods such as kriging estimators	Goovaerts, 1999
	Using simulation techniques such as sequential Gaussian simulation	Wang *et al.*, 2002a
K	Using the experimental models based on soil properties (composition of sand–silt–clay percentages, organic matter, structure, and permeability of the soil profile)	Wischmeier and Smith, 1978
	Using regression equation based on soil properties (percentages of unstable aggregates, silt, sand, and base saturation)	Angima *et al.*, 2003
	Using the published *K* values by USDA-NRCS	Soil Survey Staff, 1997
	Based on size of soil particulates	Romken, 1983
	Using geostatistical methods such as joint sequential simulation and sequential Gaussian simulation	Parysow *et al.*, 2003, Wang *et al.*, 2001
LS	Estimated from actual field measurements of length and steepness	Wischmeier and Smith, 1978
	Calculated from DEM data with various approaches	Hickey, 2000; Van Remortel *et al.*, 2001
C	Using individual soil-loss ratio values and the factor of rainfall and runoff erosivity	Renard *et al.*, 1997
	Combination of individual *C* factor from empirical models and remote-sensing classification image	Millward and Mersey, 1999
	From supervised land-cover classification of multispectral MOMS-02/D2 data	Reusing *et al.*, 2000
	Geostatistical techniques	Wang *et al.*, 2002b
	Greenness index	Ma *et al.*, 2003
P	Experimental data	Renard *et al.*, 1997

where A is the average annual soil loss in tons per acre; R is the rainfall-runoff erosivity factor; K is the soil erodibility factor; L is the slope length factor; S is the slope steepness factor; C is the cover-management factor; and P is the support practice factor. Table I summarizes the main methods for estimating these factors. Previous literature has described these methods extensively.

STUDY AREA

Rondônia has experienced high deforestation rates during the past two decades (INPE, 2002). Following the national strategy of regional occupation and development, colonization projects initiated by the Brazilian Government in the 1970s played a major role in this process (Moran, 1981). The colonists transformed the forested landscape into a patchwork of cultivated crops, pastures, successional vegetation, and remnant forests (Batistella, 2001).

The study area is located at Machadinho d'Oeste, in northeastern Rondônia (Figure 1). The climate in this study area is classified as equatorial hot and humid with tropical transition. A well-defined dry season lasts from June to August, and the annual average precipitation is 2016 mm (Rondônia, 1998). The annual average temperature is 25·5°C, and monthly averages for air moisture range from 80 to 85 per cent. The terrain is undulating, ranging from 100 to 400 m above sea-level. Several soil types were identified, mainly alfisols, oxisols, ultisols, alluvial soils, and other less spatially represented associations (Bognola and Soares, 1999; Valladares *et al.*, 2003).

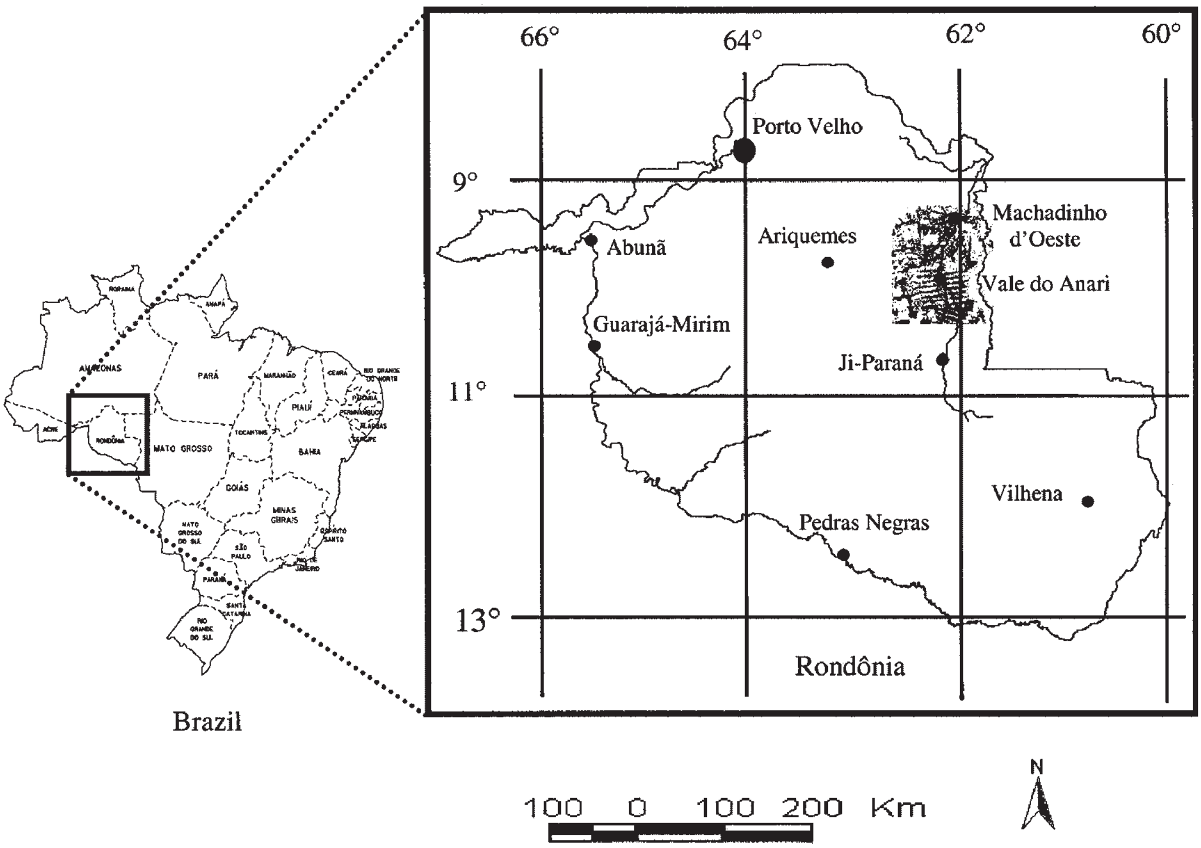


Figure 1. Location of the study area in the State of Rondônia, Brazilian Amazonia.

DATA PREPARATION

Landsat 7 ETM+ (path/row: 231/67) was acquired on 27 June 2002. The image was converted to apparent reflectance through an image-based calibration method using the gain, offset, and sun elevation angle (Markam and Barker, 1987). This image was also geometrically rectified using control points collected from topographic maps so that the image can be accurately linked to ground reference data and other ancillary data, such as soil type map and DEM data. The nearest-neighbor resampling technique was used and a root-mean-square error with less than 0·5 pixels was obtained during the image geometric rectification.

Field data collection was conducted in August 2002. Different LULC types, such as mature forest, successional forest, agroforestry (mainly coffee plantations), and pasture, were identified and their coordinates were recorded with a GPS device. These data were used as training samples for supervised classification of ETM+ data. About 10 to 15 sample plots for each class were selected. Maximum likelihood classifier (MLC) was used to classify the ETM+ data into six LULC classes: mature forest; successional forest; agroforestry; pasture; urban; and water. A majority filter with a 3 × 3 window size was used to remove the 'salt and pepper' noise in the classified image. Accuracy assessment using field data collected in August 2003 indicated an overall accuracy of approximately 90 per cent. Figure 2 shows the LULC distribution within the study area. A detailed description of LULC classification using MLC can be found in Lu *et al.* (2004).

The soil map was generated in 2003 based on interpretation of landforms and pedoforms within the landscape using Landsat TM data and aerial photographs, corroborated by soil field surveys. The representative soil profile samples were collected, described, and characterized according to the Soil Survey Manual (Soil Survey Staff,

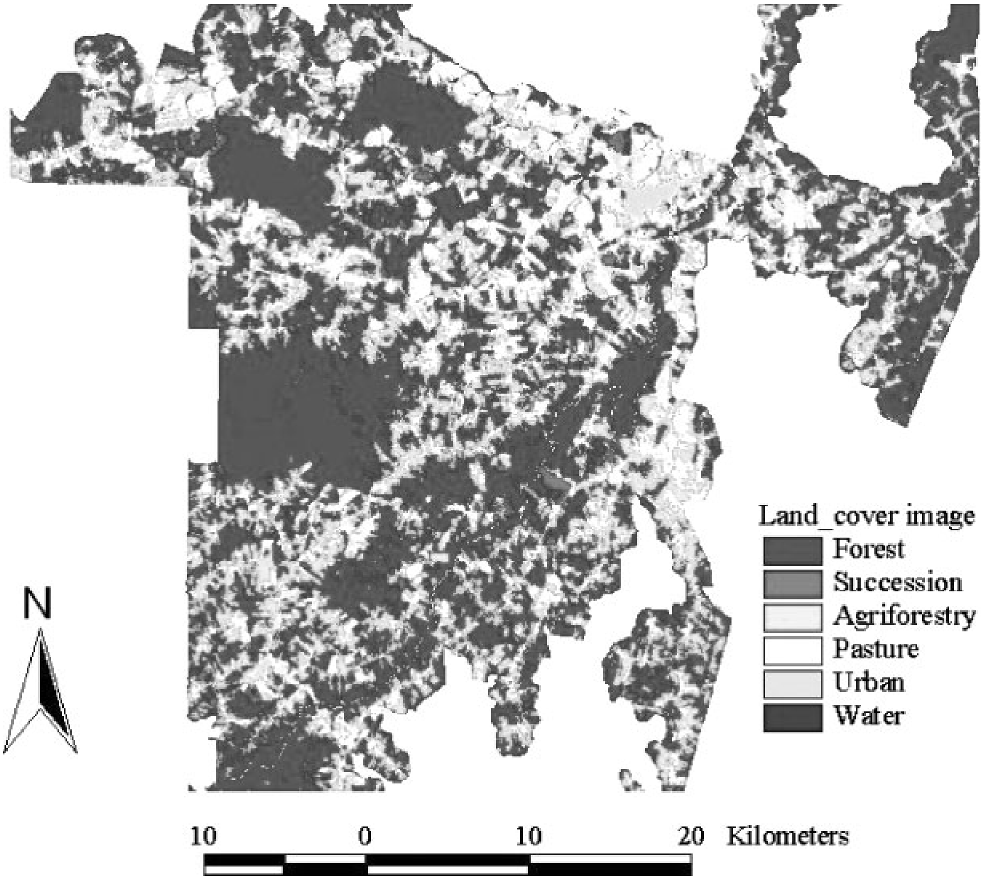


Figure 2. Land-use and land-cover classification for the study area based on ETM+ data.

1993), Lemos and Santos (1996), and Embrapa (1999). The soil types were classified according to Soil Taxonomy (Soil Survey Staff, 1998, 1999). A more detailed description of the soils in this study area can be found in Valladares *et al.* (2003) and in Embrapa (1999). Figure 3 illustrates the distribution of soil types in this study area.

Fieldwork for collecting soil sample plots was conducted in September 2002. A total of 22 samples were collected in representative points of the study area based on relief, soil, and land-cover (Valladares *et al.*, 2003). During fieldwork, the position on the relief, morphologic description, color, structure, consistency, texture, and other parameters, were recorded. In the lab, soil pH, $CaCl_2$, content of Ca, Mg, K, Na, H, Al, sum of bases, cation exchange capacity, P, organic carbon, clay, silt, and sand were analyzed. The sampling strategy was based on the representativeness of the soil's orders and suborders occurring in the study area (Soil Survey Division Staff, 1993; Lemos and Santos, 1996; Embrapa, 1999).

Contour lines, rivers, and typical points were digitized based on 1:100 000 topographic maps (UTM, South American, Zone 20), then a 30-meter spatial resolution DEM was generated using ArcGIS. Figures 4 and 5 illustrate the elevation and slope distribution for the study area. Most elevations are between 100 and 300 m and are associated with gentle slopes (less than 5 degrees).

EVALUATION OF THE SOIL EROSION RISK

Six parameters are required for the soil erosion estimation, as described previously. Because this study focuses on the evaluation of soil erosion risk, instead of estimation of actual soil erosion loss, the *R* and *P* factors were not

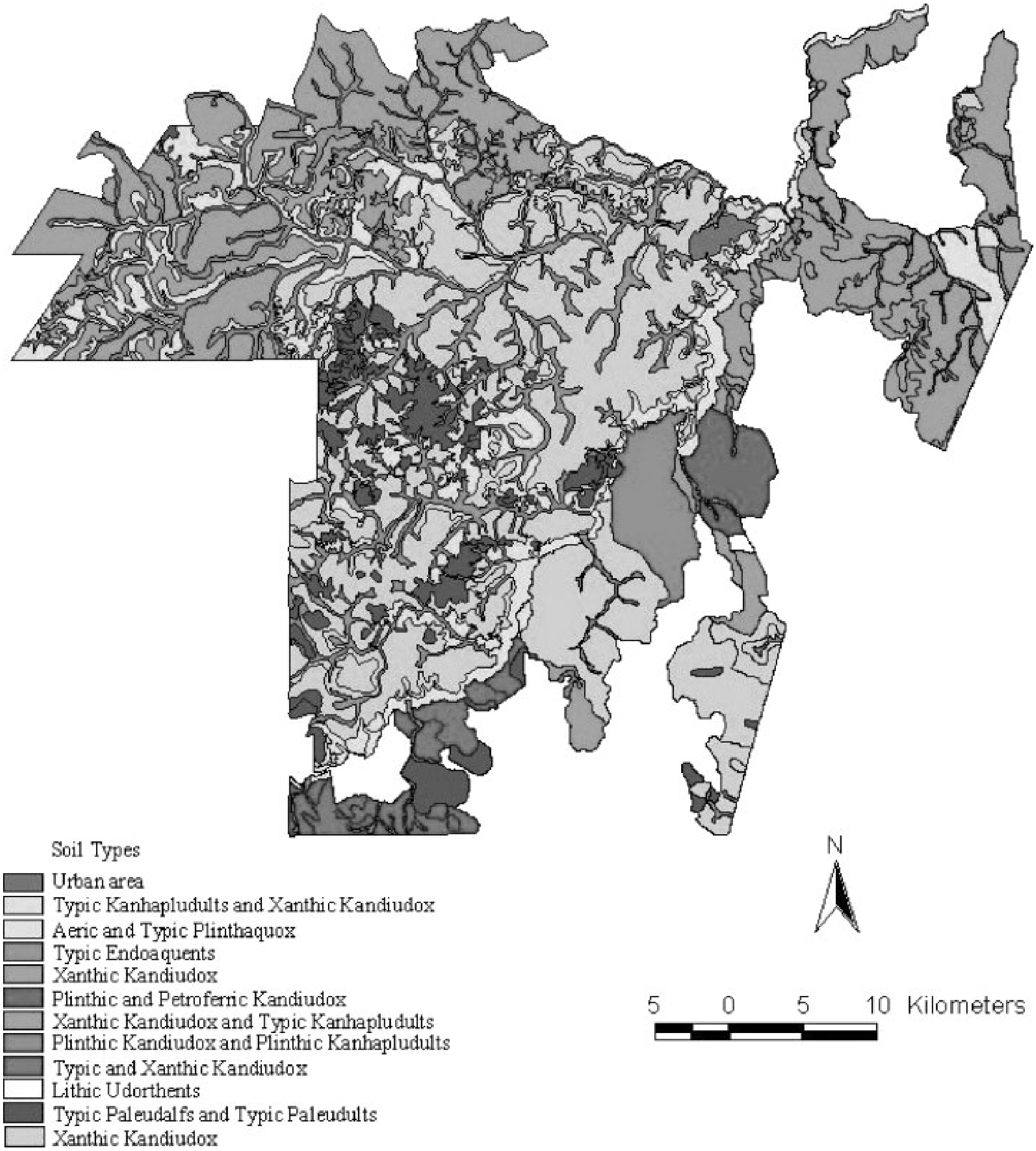


Figure 3. Spatial distribution of soil types within the study area.

used, assuming that same climatic conditions and no support practices existed within the study area. So the soil erosion risk (SER) was developed based on *K*, *LS*, and *C* factors in a simplified equation: $SER = K\ LS\ C$.

Development of the K *Factor Image*

The *K* factor is related to the integrated effects of rainfall, runoff, and infiltration on soil loss, accounting for the influences of soil properties on soil loss during storm events on upland areas (Renard *et al.*, 1997). It is often

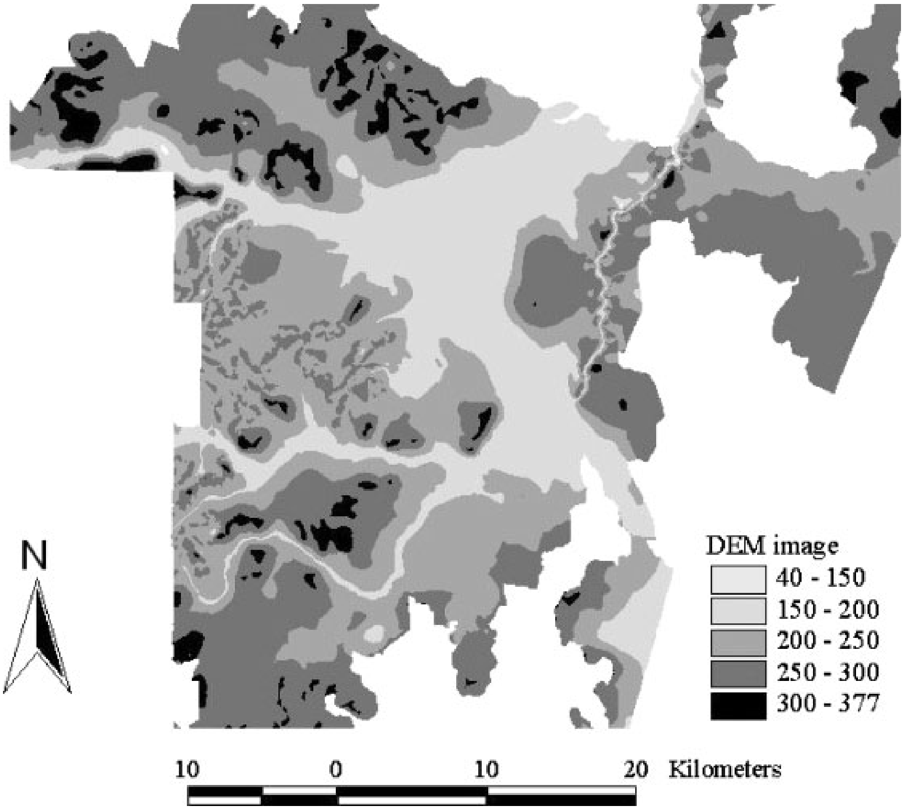


Figure 4. Grey-scale image illustrating elevation classes within the study area.

estimated through experimental equations (e.g., Equation 2) or corresponding nomographs (Wischmeier and Smith, 1978).

$$K = 2{\cdot}1 \times 10^{-6} \times M^{1{\cdot}14} \times (12 - OM) + 0{\cdot}0325 \times (P - 2) + 0{\cdot}025 \times (S - 3), \quad (2)$$

where $M = (\%silt + \%very\_fine\_sand)(100 - \%clay)$; OM = percentage of organic matter; P = permeability class; and S = structure class.

The K value for each sample plot was calculated, then each soil type was associated with a K value assuming that the same soil type has the same K value throughout the study area. Figure 6 illustrates the K factor distribution. It indicates that most of the study area has a K value of less than 0·2.

Development of the LS *Factor Image*

The *LS* factor accounts for the effect of topography on erosion in RUSLE. The slope length factor (*L*) represents the effect of slope length on erosion, and the slope steepness factor (*S*) reflects the influence of slope gradient on erosion. The common equation used for calculating *LS* is an empirical equation (see Equation 3) provided by the USDA *Agriculture Handbook* (Wischmeier and Smith, 1978).

$$LS = \left(\frac{\lambda}{22{\cdot}13}\right)^{n} (65{\cdot}41 \sin^2\theta + 4{\cdot}56 \sin\theta + 0{\cdot}065), \quad (3)$$

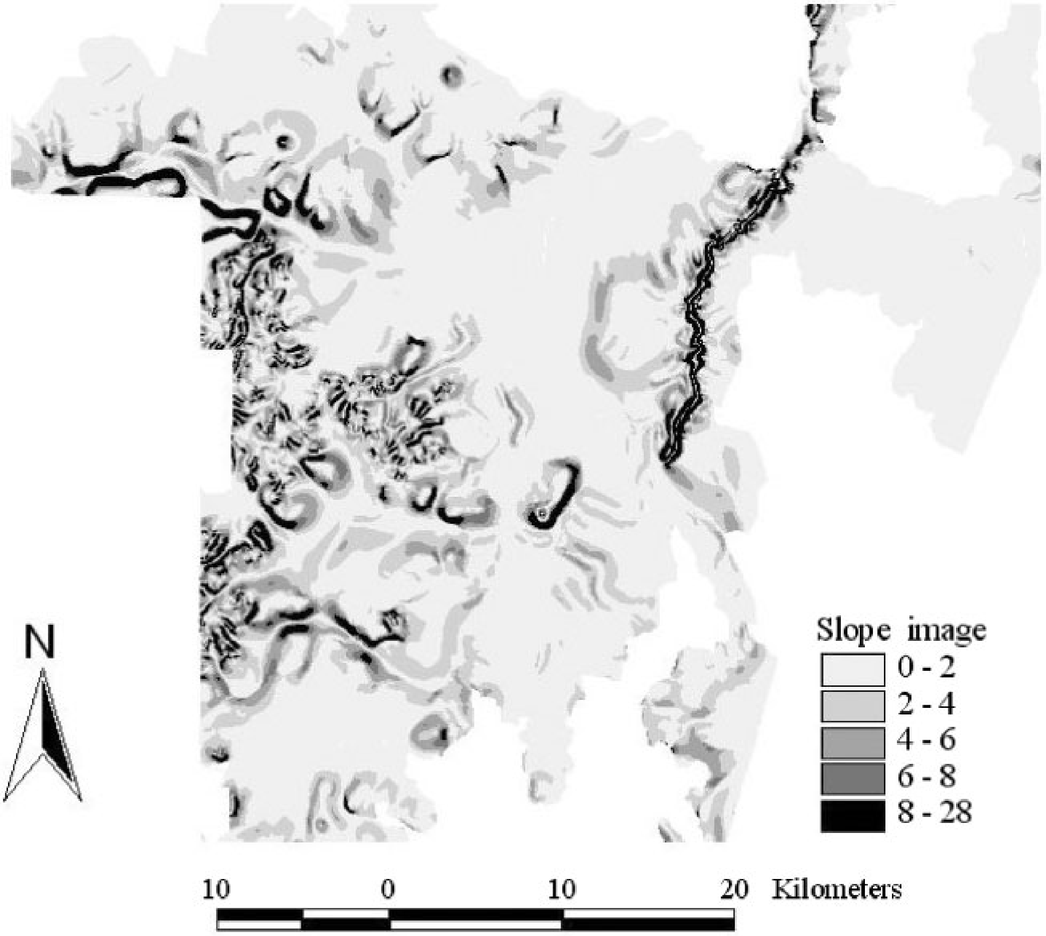


Figure 5. Grey-scale image illustrating slope classes within the study area.

where λ is the slope length in meters; θ is the angle of slope in degrees; and n is a constant dependent on the value of the slope gradient: 0·5 if the slope angle is greater than 2·86 degrees, 0·4 on slopes of 1·72 to 2·85 degrees, 0·3 on slopes of 0·57 to 1·72 degrees, and 0·2 on slopes less than 0·57 degrees.

The RUSLE-based ArcInfo Arc Macro Language (AML) program for computing the *LS* factor was developed using the raster grid cumulation and maximum downhill slope methods (Hickey, 2000; Van Remortel *et al.*, 2001) and is available at the following website: www.cwu.edu/~rhickey/slope/slope.html. Figure 7 illustrates the *LS* factor distribution. It indicates that the majority of the study area has *LS* values of less than 2·5. Some specific areas with steep slopes, such as along the river, have *LS* values of greater than 2·5.

Development of the C Factor Image

The *C* factor reflects the effects of cropping and management practices on soil erosion rates in agricultural lands and the effects of vegetation canopy and ground covers on reducing the soil erosion in forested regions (Renard *et al.*, 1997). Usually, the *C* factor is derived using empirical equations based on the measurements of many variables related to ground covers collected in the sample plots. The *C* factor values at non-sampled locations were estimated through spatial interpolation techniques. This method is often time-consuming and computer intensive. It only provides point values with limited locations. The interpolation results based on the *C* factor point values

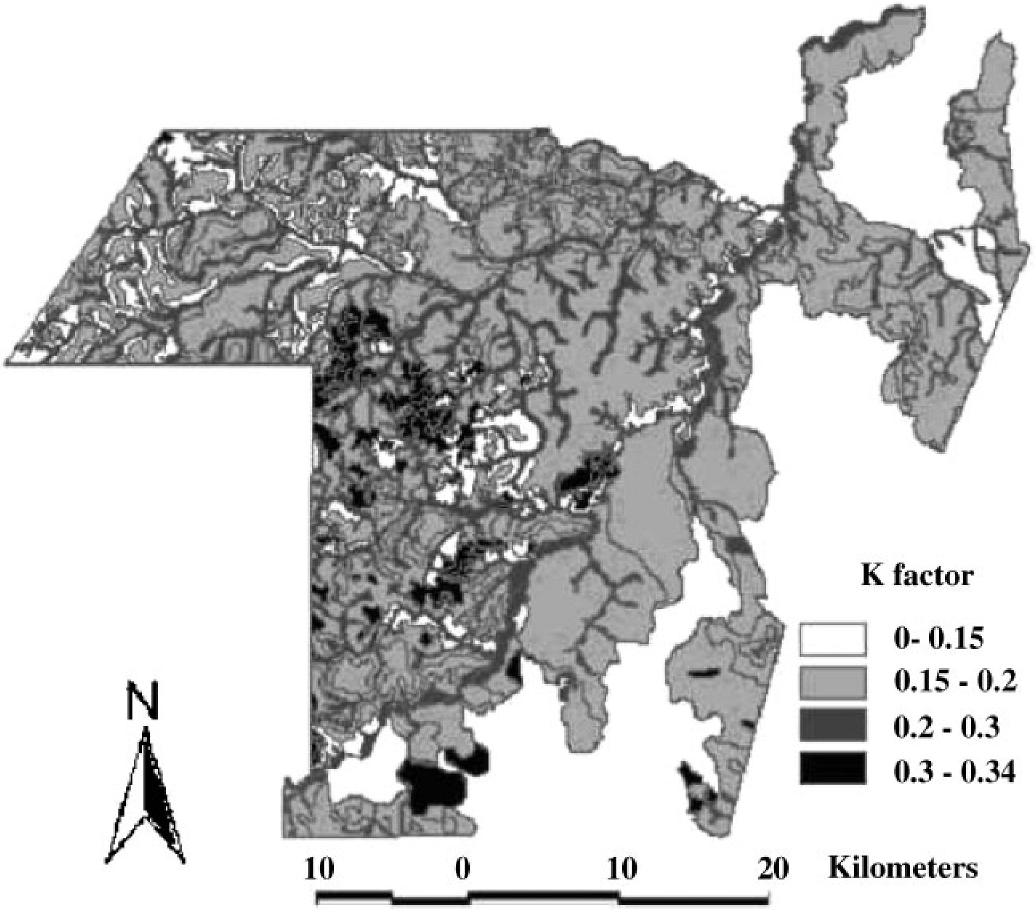


Figure 6. The soil erodibility factor developed from soil sample plots data and soil map.

could be poor due to the limited number of sample plots in complex environments (Wang *et al.*, 2002b). Therefore, remotely sensed data have been used to estimate the *C* factor distribution based on land-cover classification results (Millward and Mersey, 1999; Reusing *et al.*, 2000), assuming that the same land covers have the same *C* factor values. The result greatly depends on: (1) the details of land-cover classes and classification accuracy; and (2) the determination of a suitable *C* factor value for each class. However, the same land-cover class may have different *C* factors due to variations in vegetation density.

In this study, the *C* factor was estimated (see Equation 4) based on the fraction images from spectral mixture analysis (SMA) of Landsat ETM+ image, assuming that abundant vegetation cover associated with a complex stand structure results in less soil erosion loss, while more soil fraction associated with less vegetation cover results in higher soil erosion loss.

$$C = \frac{f_{\text{soil}}}{1 + f_{\text{gv}} + f_{\text{shade}} + f_{\text{gv}} \times f_{\text{shade}}}, \tag{4}$$

where $f_{\text{soil}}, f_{\text{gv}}$, and f_{shade} are the three fraction values of soil, green vegetation, and shade endmembers. The values of $f_{\text{soil}}, f_{\text{gv}}$, and f_{shade} parameters range from 0 to 1 and their sum equals 1. A detailed description of SMA can be

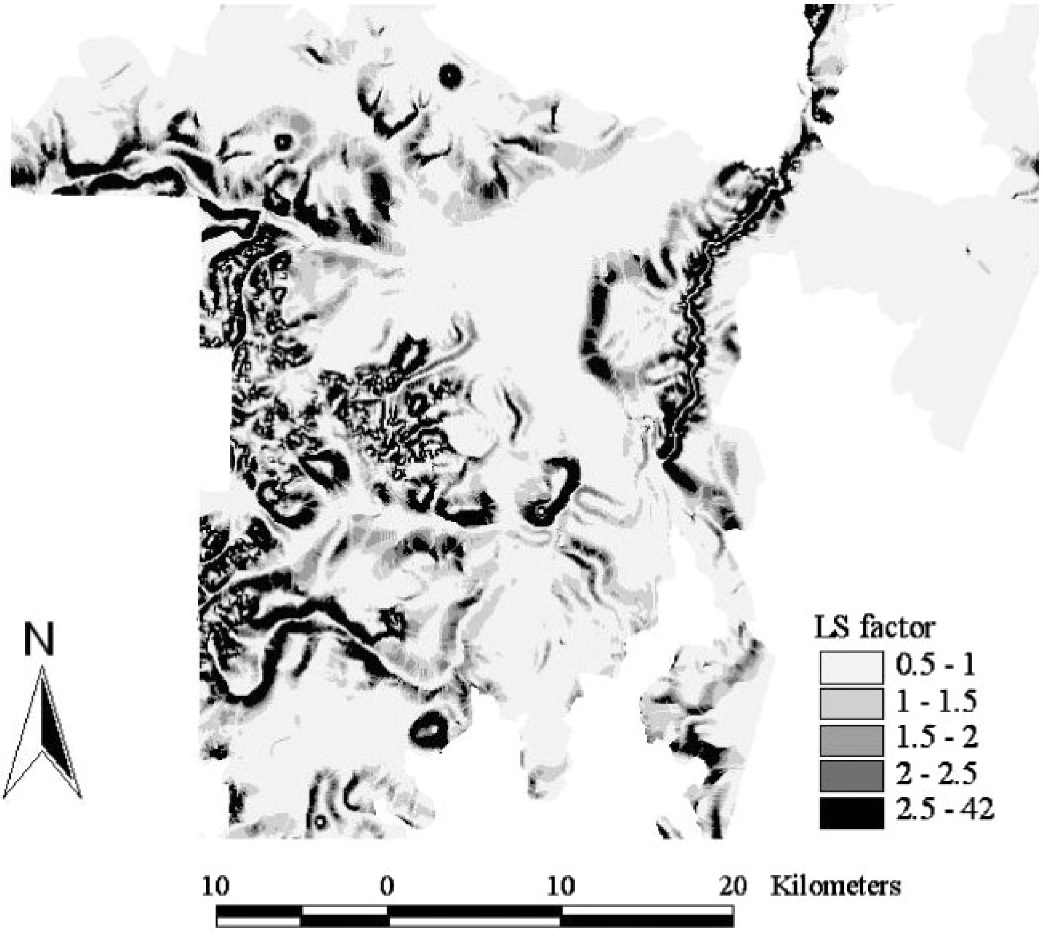


Figure 7. The topographic factor developed from the DEM data.

found in Lu *et al.* (2003). Figure 8 illustrates the *C* factor distribution. The majority of the study area has *C* values of less than 0·25. Very few areas have *C* values greater than 0·5.

Development of the Soil Erosion Risk Image

After the *K*, *LS*, and *C* factor images were developed, they were overlaid using GIS tools to generate the SER image. Five risk levels, i.e., very low, low, medium, medium-high, and high, were identified and mapped (Figure 9). The majority of the study area has very low and low risk levels. Very few areas fall in medium-high and high risk levels.

Relating the LULC Image and the SER Image

A linkage between the LULC and the SER images is valuable for understanding how different LULC classes affect soil erosion. The LULC classes were recorded as 1, 2, 3, 4, and 5, corresponding to forest, successional forest, agroforestry, pasture, and others (urban and water), respectively. The SER image was also recorded as 1, 2, 3, 4 and 5 corresponding to very low, low, medium, medium-high, and high levels, respectively. These two images were compared pixel by pixel to generate a table indicating the relationship of LULC and SER classes. Table II provides the percentage of SER with LULC classes. It indicates that mature forest, most successional forests and

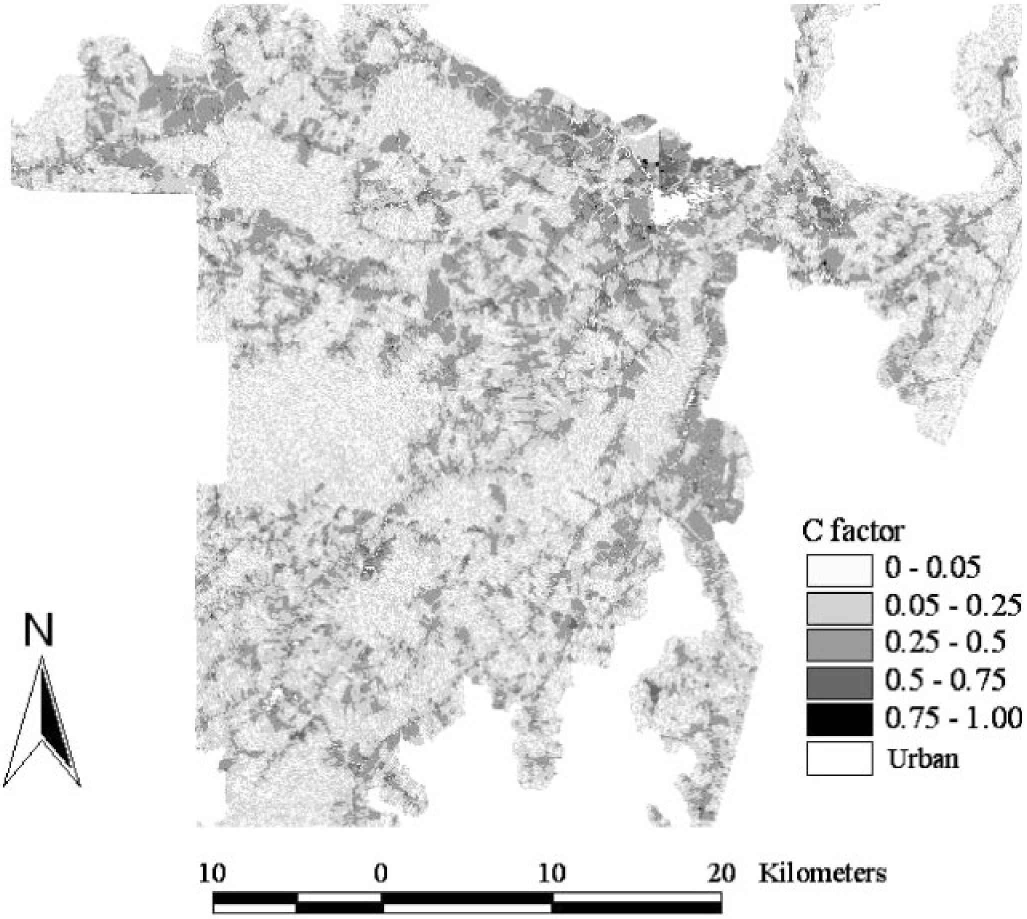


Figure 8. The cover-management factor developed using vegetation, shade, and soil fractions of ETM+ data.

agroforestry have very low or low erosion risks, but some of the pasture and agroforestry areas with limited ground cover have medium-high or high erosion risks. Table II also shows that very few areas of mature forest had medium or medium-high erosion risk. These pixels were located at the juncture of mature forests and other land covers due to the misregistration between ETM+, DEM, and soil data.

DISCUSSION AND CONCLUSIONS

RUSLE was originally developed for the USA, but also has been proven valuable for estimation of soil erosion loss in other regions of the world (Millward and Mersey, 1999; Reusing *et al.*, 2000; Angima *et al.*, 2003, Ma *et al.*, 2003). In general, RUSLE is used for estimating average annual soil erosion loss based on sample plot data. The use of remote sensing and GIS allows us to map the spatial distribution of soil erosion risk. However, because remotely sensed data capture the surface characteristics at the time of the image acquisition, caution must be taken when developing the C factor image. Calibration of the results using reference data may be necessary if it is used for estimation of absolute soil erosion loss. Also, the use of multitemporal remotely sensed data may be necessary to generate an average C factor image.

Six parameters, derived from different data sources such as DEM, soil, climate, and remotely sensed data, are used in the RUSLE. The different data sources may have different data formats, projections, data quality, and

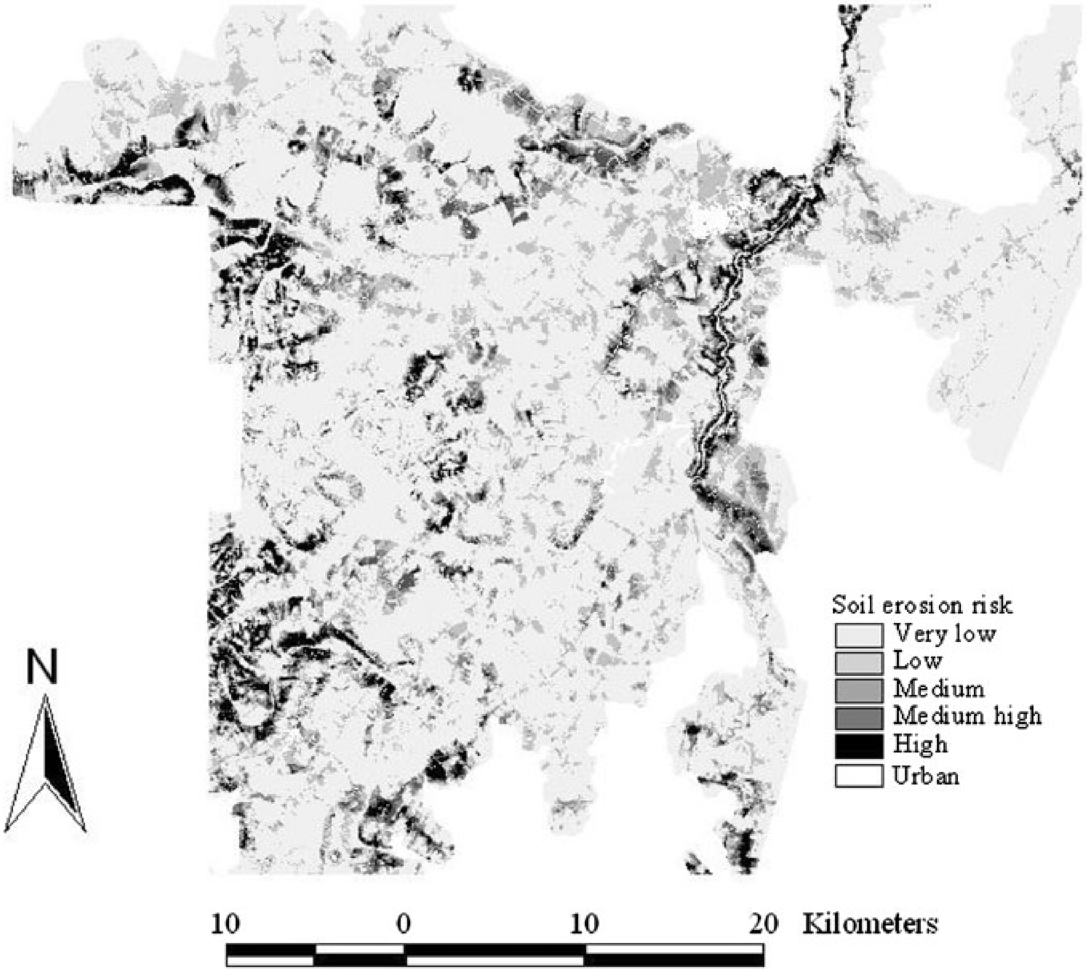


Figure 9. Erosion risk image illustrating the soil erosion conditions within the study area.

Table II. Assessment of soil erosion risk and associated land-cover distribution

LULC type	Soil erosion risk					Total (%)
	Very low (%)	Low (%)	Medium (%)	Medium-high (%)	High (%)	
Forest	43·30	2·53	0·87	0·52	0·31	47·53
Succession	9·05	0·94	0·31	0·19	0·15	10·64
Agroforestry	15·22	6·18	2·16	1·33	1·38	26·27
Pasture	2·54	7·09	2·51	1·73	1·67	15·54
Total (%)	70·11	16·74	5·85	3·77	3·51	

spatial resolution. The use of GIS provides the tools to manage and analyze these data. However, the evaluation of these data is necessary before they are used. The uncertainties regarding data sources may introduce larger uncertainties in soil erosion estimates. Great attention should be paid to the evaluation and preprocessing of data sources, such as data interpolation, conversion, and registration.

Estimation of soil erosion loss in a large area is often difficult, as well as its validation. Although this paper focuses on the evaluation of soil erosion risk, validation using reference data is also valuable. For example, if reference data are available, the classification of soil erosion risk and the identification of thresholds for each risk level will be more appropriate.

In summary, this study provides an approach for the evaluation of soil erosion risk in Brazilian Amazonia based on a combination of RUSLE, remote sensing, and GIS. This is an effective way to map the spatial distribution of soil erosion risks in a large area. The methods and results described in this article are valuable for understanding the relationship between soil erosion risk and LULC classes and are useful for managing and planning land use that will avoid land degradation. For Brazilian Amazonia, such topics are very important due to current activities involving forest conversion to other land covers.

ACKNOWLEDGEMENTS

The authors wish to thank the National Science Foundation (grants 95-21918 and 99-06826), the National Aeronautics and Space Administration (grant N005-334), and Embrapa Satellite Monitoring for their support, which provided funds for the research that led to this article. This research is part of the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) program, LC-09, which is examining the human and physical dimensions of land-use and land-cover change.

REFERENCES

Adinarayana J, Rao KG, Krishna NR, Venkatachalam P, Suri JK. 1999. A rule-based soil erosion model for a hilly catchment. *Catena* **37**: 309–318.

Ananda J, Herath G. 2003. Soil erosion in developing countries: a socio-economic appraisal. *Journal of Environmental Management* **68**: 343–353.

Angima SD, Stott DE, O'Neill MK, Ong CK, Weesies GA. 2003. Soil erosion prediction using RUSLE for central Kenyan highland conditions. *Agriculture, Ecosystems, and Environment* **97**: 295–308.

Bartsch KP, van Miegroet H, Boettinger J, Dobrwolski JP. 2002. Using empirical erosion models and GIS to determine erosion risk at Camp Williams. *Journal of Soil and Water Conservation* **57**: 29–37.

Batistella M. 2001. *Landscape change and Land-Use/Land-Cover dynamics in Rondônia, Brazilian Amazonia*. CIPEC Dissertation Series, No. 7. Center for the Study of Institutions, Population, and Environmental Change (CIPEC), Indiana University: Bloomington, Indiana.

Batistella M, Robeson S, Moran EF. 2003. Settlement design, forest fragmentation, and landscape change in Rondônia, Amazonia. *Photogrammetric Engineering and Remote Sensing* **69**: 805–812.

Boggs G, Devonport C, Evans K, Puig P. 2001. GIS-based rapid assessment of erosion risk in a small catchment in the wet/dry tropics of Australia. *Land Degradation & Development* **12**: 417–434.

Bognola IA, Soares AF. 1999. *Solos das 'glebas 01, 02, 03 e 06' do Município de Machadinho d'Oeste, RO.* Pesquisa em Andamento, No. 10. Embrapa Monitoramento por Satélite: Campinas, Brazil, 7.

Cerri CEP, Dematte JAM, Ballester MVR, Martinelli LA, Victoria RL, Roose E. 2001. GIS erosion risk assessment of the Piracicaba River Basin, southeastern Brazil. *Mapping Sciences and Remote Sensing* **38**: 157–171.

D'Ambrosio D, di Gregorio S, Gabriele S, Gaudio R. 2001. A cellular automata model for soil erosion by water. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* **26**: 33–39.

Embrapa. 1999. *Sistema brasileiro de classificação de solos*. Centro Nacional de Pesquisa de Solos: Rio de Janeiro.

Fullen MA. 2003. Soil erosion and conservation in northern Europe. *Progress in Physical Geography* **27**: 331–358.

Goovaerts P. 1999. Using elevation to aid the geostatistical mapping of rainfall erosivity. *Catena* **34**: 227–242.

Hickey R. 2000. Slope angle and slope length solutions for GIS. *Cartography* **29**: 1–8.

INPE. 2002. *Monitoring of the Brazilian Amazonia Forest by Satellite 2000–2001*. Instituto Nacional de Pesquisas Espaciais: Jose dos Campos, Brazil.

Lal R. 1998. Soil erosion impact on agronomic productivity and environment quality: critical reviews. *Plant Sciences* **17**: 319–464.

Lal R. 2001. Soil degradation by erosion. *Land Degradation & Development* **12**: 519–539.

Lemos RC, Santos RD. 1996. *Manual de descrição e coleta de solos no campo*, 3rd edn. SBCS/Embrapa—CNPS: Campinas, Brazil.

Lu D, Moran E, Batistella M. 2003. Linear mixture model applied to Amazonian vegetation classification. *Remote Sensing of Environment* **87:** 456–469.

Lu D, Mausel P, Batistella M, Moran E. 2004. Comparison of land-cover classification methods in the Brazilian Amazonia basin. *Photogrammetric Engineering and Remote Sensing* **70**: 723–731.

Ma JW, Xue Y, Ma CF, Wang ZG. 2003. A data fusion approach for soil erosion monitoring in the Upper Yangtze River Basin of China based on Universal Soil Loss Equation (USLE) model. *International Journal of Remote Sensing* **24**: 4777–4789.

Markham BL, Barker JL. 1987. Thematic mapper bandpass solar exoatmospheric irradiances. *International Journal of Remote Sensing* **8**: 517–523.

Mati BM, Veihe A. 2001. Application of the USLE in a savannah environment: comparative experiences from east and west Africa. *Singapore Journal of Tropical Geography* **22**: 138–155.

Mikhailova EA, Bryabt RB, Schwager SJ, Smith SD. 1997. Predicting rainfall erosivity in Honduras. *Soil Science Society of America Journal* **61**: 273–279.

Millward AA, Mersey JE. 1999. Adapting the RUSLE to model soil erosion potential in a mountainous tropical watershed. *Catena* **38**: 109–129.

Moran EF. 1981. *Developing the Amazonia*. Indiana University Press: Bloomington, Indiana.

Nearing MA, Foster GR, Lane LJ, Finkner SC. 1989. A process-based soil erosion model for USDA-Water Erosion Prediction Project Technology. *Transactions of the ASAE* **32**: 1587–1593.

Parysow P, Wang G, Gertner GZ, Anderson AB. 2003. Spatial uncertainty analysis for mapping soil erodibility based on joint sequential simulation. *Catena* **53**: 65–78.

Renard KG, Fremund JR. 1994. Using monthly precipitation data to estimate the *R*-factor in the revised USLE. *Journal of Hydrology* **157**: 287–306.

Renard KG, Foster GR, Weesies GA, McCool DK, Yoder DC. 1997. *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)*. Handbook #703. US Department of Agriculture: Washington, DC; 404.

Reusing M, Schneider T, Ammer U. 2000. Modeling soil erosion rates in the Ethiopian Highlands by integration of high resolution MOMS-02/D2-stereo-data in a GIS. *International Journal of Remote Sensing* **21**: 1885–1896.

Romken MJM. 1983. The soil erodibility factor: a perspective. *Soil Erosion and Conservation* **10**: 445–461.

Rondônia. 1998. *Diagnóstico Sócio-Econômico do Estado de Rondônia e Assistência Técnica para Formulação da Segunda Aproximação do Zoneamento Sócio-Econômico-Ecológico—Climatologia*, Vol. 1. Governo de Rondônia/PLANAFLORO: Porto Velho, Brasil.

Shakesby RA, Coelho COA, Schnabel S, Keizer JJ, Clarke MA, Contador JFL, Walsh RPD, Fereira AJD, Doerr SH. 2002. A ranking methodology for assessing relative erosion risk and its application to Dehesas and Montados in Spain and Portugal. *Land Degradation & Development* **13**: 129–140.

Shen DY, Ma AN, Lin H, Nie XH, Mao SJ, Zhang B, Shi JJ. 2003. A new approach for simulating water erosion on hillslopes. *International Journal of Remote Sensing* **24**: 2819–2835.

Soil Survey Staff. 1993. *Soil Survey Manual*. USDA-SCS Agriculture Handbook, Vol. 18. USDA Soil Conservation Service: Washington, DC.

Soil Survey Staff. 1997. *National Soil Survey Handbook*, Title 430-VI. USDA Natural Resources Conservation Service: Washington, DC.

Soil Survey Staff. 1998. *Keys to Soil Taxonomy*, 8th edn. USDA Natural Resources Conservation Service: Washington, DC.

Soil Survey Staff. 1999. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. Agriculture Handbook 436. USDA Natural Resources Conservation Service: Washington, DC.

Thiam AK. 2003. The causes and spatial patterns of land degradation risk in southern Mauritania using multitemporal AHVRR-NDVI imagery and field data. *Land Degradation & Development* **14**: 133–142.

Valladares GS, Bognola IA, Gouvêa JRF. 2003. *Levantamento de Reconhecimento de Solos de Média Intensidade da Gleba Machadinho, RO*. Documentos 30. Embrapa Monitoramento por Satélite: Campinas, Brazil.

Van Remortel R, Hamilton M, Hickey R. 2001. Estimating the LS factor for RUSLE through iterative slope length processing of digital elevation data within ArcInfo Grid. *Cartography* **30**: 27–35.

Veihe A, Rey J, Quinton JN, Strauss P, Sancho FM, Somarriba M. 2001. Modelling of event-based soil erosion in Costa Rica, Nicaragua and Mexico: evaluation of the EUROSEM model. *Catena* **44**: 187–203.

Vrieling A, Sterk G, Beaulieu N. 2002. Erosion risk mapping: a methodological case study in the Colombian eastern plains. *Journal of Soil and Water Conservation* **57**: 158–163.

Wang G, Gertner GZ, Liu X, Anderson A. 2001. Uncertainty assessment of soil erodibility factor for revised universal soil loss equation. *Catena* **46**: 1–14.

Wang G, Gertner G, Singh V, Shinkareva S, Parysow P, Anderson A. 2002a. Spatial and temporal prediction and uncertainty of soil loss using the revized universal soil loss equation: a case study of the rainfall–runoff erosivity *R* factor. *Ecological Modeling* **153**: 143–155.

Wang G, Wente S, Gertner GZ, Anderson A. 2002b. Improvement in mapping vegetation cover factor for the universal soil loss equation by geostatistical methods with Landsat Thametic Mapper images. *International Journal of Remote Sensing* **23**: 3649–3667.

Wang G, Gertner G, Fang S, Anderson AB. 2003. Mapping multiple variables for predicting soil loss by geostatistical methods with TM images and a slope map. *Photogrammetric Engineering and Remote Sensing* **69**: 889–898.

Wilson JP, Lorang MS. 2000. Spatial models of soil erosion and GIS. In *Spatial Models and GIS: New Potential and New Models*, Fotheringham AS, Wegener M (eds). Taylor & Francis: Philadelphia, PA; 83–108.

Wischmeier WH, Smith DD. 1978. *Predicting Rainfall Erosion Losses—A Guide to Conservation.* Agricultural Handbook 537. US Department of Agriculture: Washington, DC.