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Full Length Research Paper

Natural and eco-environmental vulnerability assessment through multi-temporal satellite data sets in Apodi valley region, Northeast Brazil

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The objective of this study was to improve our understanding of vulnerability and environmental change; its causes basically show the intensity, its distribution and human-environment effect on the ecosystem in the Apodi Valley Region, This paper identify, assess and classify vulnerability and environmental change in the Apodi valley region using a combined approach of landscape pattern and ecosystem sensitivity. Models were developed using the following five thematic layers: Geology, geomorphology, soil, vegetation and land use/cover, by means of a geographical information systems (GIS)-based on hydro-geophysical parameters. In spite of the data problems and shortcomings, using ESRI's ArcGIS 9.3 program, the vulnerability score, to classify, weight and combine a number of 15 separate land cover classes to create a single indicator provides a reliable measure of differences (6 classes) among regions and communities that are exposed to similar ranges of hazards. Indeed, the ongoing and active development of vulnerability concepts and methods have already produced some tools to help overcome common issues, such as acting in a context of high uncertainties, taking into account the dynamics and spatial scale of asocial-ecological system, or gathering viewpoints from different sciences to combine human and impact-based approaches. Based on this assessment, this paper proposes concrete perspectives and possibilities to benefit from existing commonalities in the construction and application of assessment tools.

Key words: Vulnerability, land use/cover, ecosystem, remote sensing, GIS.

INTRODUCTION

The study region is located in an area of high environmental sensitivity zone; subject to great pressure of human activities, resulting in an environmental degradation mainly due to its most economic activities. This coastal zone can be considered an area of huge contrasts. On the one hand, there are intensively urbanized regions, port systems, seaside tourist resorts as well as industrial, salt, fishing and oil exploitation activities. On the other hand, vast areas still exist with a low population density and well-preserved ecosystems of considerable environmental value. Recently, however, these naturally intact parts of the coastal system are also becoming a focus of an accelerated rate of increasing occupation and utilization.

Active and passive remote sensing has emerged as a viable mode for vulnerability and environmental monitoring due to its unique target interaction as well as all weather capability, which allows the surface monitoring through clouds. Microwave emission is mainly influenced by the dielectric and roughness properties of the targets (Ulaby and Bush, 1976). In the recent era, wide spectra of satellite data are available varying in (1) techniques (active/passive, radiometer/ scatterometer), (2) spatial resolution from few metres to kilometres (3) spectral range and (4) viewing geometry. Satellite imagery has been well utilized in natural science to measure quailtative and quantitative land-cover changes (Vela et al., 2008). Qualitative changes in landscapes can be attributed to either natural or human factors (Paul et al.,

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2002). Lunetta and Balogh (1999) have evaluated the application of moderate spatial (30 m) and spectral resolution satellite imagery and digital image analysis technology in ensuring the potential jurisdictional of landscape. Remote sensing technology has been extensively used in landscape ecosystem studies (Rodriguez et al., 2007), such as the analysis of hydrology and land cover changes (Myneni et al., 2002; Chen, 2002) used Landsat images to draw the land-cover maps and to analyze the change of landscape area. Landsat MSS, TM, and SPOT-XS are common data types for landscape classification and its temporal-spatial dynamic change (Myneni et al., 2002; Paul et al., 2002).

Turner et al. (2003) draw out the interaction between social and environmental systems as both a context and driver for vulnerability. Birkmann (2006) attempts to combine these approaches in the BBC conceptual framework and aims to show vulnerability within a dynamic process. Most recently, and influenced by the use of vulnerability in the Intergovernmental Panel on Climate Change (IPCC), vulnerability is being refined and structured according to the IPCC definition as composed of three factors: (1) Exposure, (2) Susceptibility, and (3) Coping or adaptive capacity. These terms cover the same range of input variables as had been used by existing vulnerability analyses, but are associated with different and more detailed concepts. This is in itself an important way in which climate change science has brought new perspectives to natural disaster risk reduction. In this formulation, exposure equates with the impact side of vulnerability, susceptibility with the fragility of the element exposed, and capacity with the ability of risk elements to face the adverse effects of a hazardous event (coping/adaptation). As this introduction indicates, the term vulnerability is now a central concept in a variety of other research disciplines and it is conceptualized in very different ways by scientists from different knowledge domains and even within the same domain (Fu¨ssel, 2007).

In this paper, we propose a method for assessing the vulnerability of socio-ecological systems that is explicitly linked to multiple stakeholder values enabling multiple assessments of vulnerability in the same or different locations. Five thematic layers we use (geology, geomorphology, soil, vegetation and land use) to define vulnerability and environmental change. Research shows the impact assessments of vulnerability of the human-environment system under such environmental changes and gives the answer of important multidisciplinary policy relevant questions such as: which are the main regions or sectors that are vulnerable to environmental change? How do the vulnerabilities of two regions compare? Which scenario is the least, or most, harmful for a given region or sector?

The model uses a new approach to ecosystem assessment by integrating the potential impacts in a vulnerability assessment, which can help answer multidisciplinary questions, such as those listed above. Research presents the vulnerability assessment of the geology, geomorphology, soil, vegetation and land use scenarios. Fifteen land use types, discussed in detail, can be related to a range of ecosystem services. For instance, forest area is associated with wood production and designated land with outdoor recreation but forest area encroached by the oil and natural gas exploration and also for agriculture purpose by the local peoples then it is again encroached by the salt industry and now since last ten years it is slowly replaced by the shrimp farms due to market demand. So directly applying the vulnerability methodology to the land use change scenarios helps in understanding land use change impacts across the Apodi Valley Region, Northeast Brazil. Scatter plots summarizing impacts per principal unit zone, help in interpreting how the impacts of the scenarios differ between ecosystem services and the environments.

Another basic issue for the evaluation a model is to assign weights to each factor according to its relative effects of factors considered on the eco-environmental vulnerability in a thematic layer. The analytic hierarchy process, a theory dealing with complex technological, economical, and socio-political problems (Saaty and Vargas, 1991), is an appropriate method for deriving the weight assigned to each factor. The degree of membership within different levels of different indices was integrated using weight and the total degrees of membership for different thematic layers were used to calculate the whole study area natural and environmental vulnerability. The application of subjective weightings on the one hand gives us some indication of how the relative importance of different factors might vary with context, and can also tell us how sensitive eco-environmental vulnerability ratings are to perceptions of vulnerability in the expert community.

METHODOLOGY

Study area

The study area is located on the northwestern portion of Rio Grande do Norte State, along the Apodi River valley. The Apodi River originates nearby Apodi city in the semiarid region on the Northeast Brazil, and flows NE through Mossoro, Areia Branca and Grossos districts of Rio Grande do Norte State, and discharges directly into the Atlantic Ocean (Figure 1). The geographic coordinates are limited by latitude 04°55'46".77 to 05°13'39".41 south and longitude 37°01'30".79 to 37°22'42".42 East. The area has semiarid tropical type of climate, with mean annual temperature about 28°C. The average rainfall of 700 to 900 mm/year is mostly concentrated within February to April and can fall at high intensities, but is accompanied by very high potential evaporation (in excess of 2,000 mm/year).

METHODS

In the present study, to take the dual advantages, both conventional and remotely sensed data were used. The main remote sensing

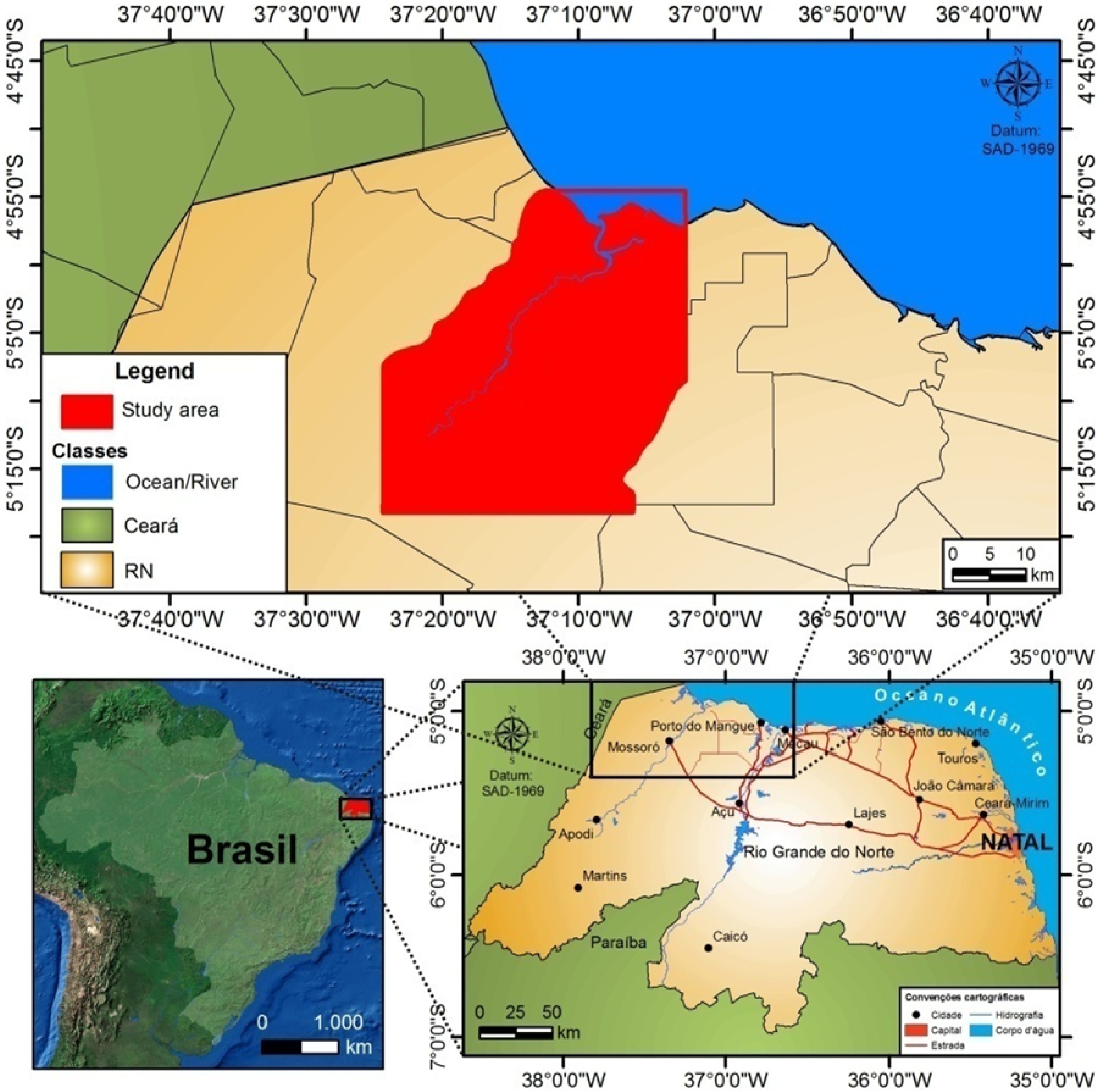

Figure 1. Study area location on Rio Grande do Norte State, Northeast Brazil.

products used in this research work were: Orbital images of Landsat TM, ETM+, Spot 4-HRVIR, IKONOS, CBERS 2B and SRTM data. Topographic sheets were used SB-24-XB-IV, SB-24-XDI, XDI-SB-24-1-2 and MI-897-2. Using UTM cartographic projection Zone 24S - Datum SAD-69 and the root mean square (RMS) were less than 1.0 m. Trimble hand held GPS with 10 m accuracy was used to map study area. All secondary data were collected from IDEMA, IBGE and metrological department of RN, Brazil.

Maps of geo-environmental units (geology, geomorphology, soils, vegetation and land use/cover) were prepared on scale of 1:150.000, from the interpretation of satellite imagery using Arc GIS 9.3 software and field applications. We used different weights for the different landscape units based on the concept of stability of each unit, considering to the analysis concept of (Ecodinâmica, 1977), where stability was classified according to Table 1. The weights of a landscape unit indicate the importance of any factor in relation to others (Xavier-Da-Silva et al., 2001). Spatial analysis techniques were used to integrate the thematic maps. The memberships of each thematic layer were based on the sensitivity or its effectiveness in the study area (Grigio et al., 2004).

For the allocation of the values of each theme class was required establish some criteria for the definition of each class. Which were used by Barbosa (1997). The degree of vulnerability to each prescribed class was distributed in a range from 0.0 to 3.0 (Ex. wetland and coast plains 1.0, barriers formation, fixed dunes, settlements and quartz sand 2.0, temporary and permanent culture 1.8, production of marine shrimp 2.8, temporary pond 1.0, ocean/river and area without vegetation 0.0, oil and gas exploration well 2.9, Salina 2.7, thermoelectric, fluvial-marine plain, alluvial and *eluvial* deposits 2.5, Jandaíra formation, fruit corps and dune vegetation 1.5, fluvial-estuarine plain, sodic soil, mangrove and carnauba palm tree 3.0 etc.). The value 1.0 prevails pedogenesis, in 2.0 a balance between pedogenesis and morphogenesis, and 3.0 prevails morphogenesis. This criterion was used for maps geomorphology, geology and simplified soil/soil system. For case of vegetation/biodiversity map, the criterion was established: 3.0

Table 1. Stability values of landscape units.

Unit	Pedogenesis / morphogenesis relation	Value
Stable	Prevails pathogenesis	1.0
Intermediate	Balance between pedogenesis and morphogenesis	2.0
Unstable	Prevails morphogenesis	3.0

Environments with very low species diversity/incipient formations, usually pioneers, 2.0 for environments with low diversity of species, corresponding to formations in the intermediate stage, and finally, to 1.0 in stage environments advanced-climax, that is, with high species diversity. For the water surface, tide channel was given a degree of vulnerability of 1.0 for geomorphology, geology and simplified soil/soil system maps. For vegetation/biodiversity maps and land use and land cover, was awarded the 3.0 degree of vulnerability.

To develop a natural vulnerability map (Figure 3), we correlated the natural aspects of geology, geomorphology, soils and vegetation. Natural vulnerability map has been integrated with the land use and land cover map to generate the environmental vulnerability map (Figure 7), considering the anthropogenic influence in the area. The degree of vulnerability varies from 0 to 3 and is ranked unrated, very low, low, medium, high and very high. The weights of compensation indicate the importance of any factor in relation to others, as can be seen in the formula below for natural vulnerability map.

[(Theme 1) + (Theme 2) + (Theme 3) + (Theme 4)] /4

Where theme 1 is geomorphology map, theme 2 is simplified geological map, theme 3 is soil/soil system map, and theme 4 is vegetation/biodiversity map.

The result mean was distributed in six natural vulnerability classes: Unrated/potential (less than or equal to 0.99); very low (from 1.0 to 1.39); low (1.40 to 1.75); medium (from 1.76 to 1.99); high (from 2.0 to 2.60), and very high (greater than or equal to 2.61).

To obtain the environmental vulnerability map was carried out crossing between the map of natural vulnerability and the statement of use and occupation of soil in the year 2008. The criteria established for the land use map were focused on main degree and type of human disturbance found in the study area. For beam, we adopted the same scale applied previously, Ex. from 1 to 3, with range of 0.1 (Table 1). We gave weights of each factor according to their sensitivity (Barbosa, 1997) and then membership according to following formula to generate environmental vulnerability map.

0.2 × (Theme 1) + 0.1 × (Theme 2) + 0.1 × (Theme 3) + 0.1 × (Theme 4) + 0.5 × (Theme 5)

Where theme 1 is geomorphology map, theme 2 is simplified geological map, theme 3 is soil/soil system map, theme 4 is vegetation/biodiversity map, and theme 5 is land use /land cover map. In the case of the environmental vulnerability map, after the crossing, calculated the average weighted of the vulnerability of each class, and divided into six environmental vulnerability classes: Unrated (less than or equal to 0.99); very low (from 1.0 to 1.39); low (1.4 to 1.50); medium (from 1.51 to 1.99); high (from 2.0 to 2.59), and very high (greater than or equal to 2.60).

LAND USE SCENARIOS IN VULNERABILITY ASSESSMENT

Natural and environmental vulnerability is most easily associated with types of land use and ecosystem like food production can be directly related to agricultural land use, shrimp farm, salt and fruit industry in the study area, fiber or timber production to forestry and cropland, and energy production to the area used for bio-energy crops and oil and natural gas exploration, costal and industrial area. In the land use change scenarios, reductions in agricultural land are an effect of intensification of production in optimal regions. Hence, total food or energy production or exploration availability will not decrease. Nevertheless, decreasing regional production does have consequences for consumers, because regional products are associated with variation as well as traditional foods or other productions. Furthermore, regionally produced food or energy is frequently associated with high quality and safety standards. A more limited choice of productions, mass-produced in optimal locations will be seen as negative impacts by parts of society. The actual ecosystem service provision, in crop yield, timber or energy increment, greatly depends on biophysical growing conditions. However, as previously discussed, in order to compare ecosystem services across the study area, differences caused by inherently different environments were removed using the stratification. Therefore, for the vulnerability concept used here, the land use types form appropriate indicators for ecosystem service provision.

Land use/cover change detection and accuracy assessment

Land cover classes are typically mapped from digital remotely sensed data through the process of a supervised digital image classification (Campbell, 2002). The overall objective of the image classification procedure is to automatically categorize all pixels in an image into land cover classes or themes (Lillesand et al., 2004). The maximum likelihood classifier quantitatively evaluates both the variance and covariance of the category spectral response patterns when classifying an unknown pixel so that it is considered to be one of the most accurate classifier since it is based on statistical parameters. Supervised classification was done using ground checkpoints and digital topographic maps of the study area. The area was classified into fifteen main classes: agriculture, wetland, forest, exposed soil, fixed dunes, industrial area, ponds, mangroves, mobile dunes, ocean/river, petroleum area, salt area, shrimp farm, stabilized pond and urban area.

Following the classification of imagery from the individual years, a multi-date post-classification comparison change detection algorithm was used to determine changes in land cover in four intervals, 1986 to 1989, 1989 to 1996, 1996 to 2001, and 2001 to 2009. This is perhaps the most common approach to change detection (Jensen, 2004) and has been successfully used by Yang (2002) to monitor land use changes in the Atlanta, Georgia area. The post-classification approach provides "from-to" change information and the kind of landscape transformations that have occurred can be easily calculated and mapped.

Then accuracy assessment was carried out using 85 points, 65 point from field data and 20 points existing topographic maps and land cover map. The location of the 85 points was chosen using random stratified method to represent different land cover classes of the area. In order to increase the accuracy of land cover mapping of the two images, ancillary data and the result of visual interpretation was integrated with the classification result using GIS in order to improve the classification accuracy of the classified image.

Land cover change detection results/statistics

Classification maps were generated for all five years (Figure 2) and the individual class area and change statistics for the five years are summarized in Table 2 from 1986 to 2009. In 1986 urban area was 18.74 km^2 (1.36%) but in 2009 it is increased and reach approximately 53.50 Km^2 (3.88%), while agriculture area was firstly increased from 1986 (243.20 Km^2 (17.05%)) to 1996 (244.62 Km^2 (19.58%)) but after it decreased till 2009 (189.51 Km^2, 13.8%), forest area also decreased from 1986 (692.93.20 Km^2 (50.46%)) to 2001 (616.46 Km^2 (45.40%)) but now due to government interference or protection rules, it is again increased till 2009 (724.29 Km^2 (52.76%)), and wetland area was 151.83 Km^2 (11.05%) in 1986 but now it´s only 48.52 Km^2 (3.51%). Although the extent of wetlands may change from year to year due to varying precipitation and temperature, the variation in wetland area is also likely due to classification errors. However, the small fluctuations in water are believed to be related to varying lake levels given the high classification accuracy for water.

In Apodi Valley region first time industrial area show in 1996 approximately 0.57 Km^2 (0.04%) and continuously increased and reach up to 3.30 Km^2 (0.24%). The biggest change is come in petroleum area, it was 1.11 Km^2 (0.08%) in 1986 and now 77.85 Km^2 (5.67%) still continuously increasing. Salt area is approximately stable but now due to market demand slowly replace by the shrimp farms since 2001. Fixed dunes continuously decreased and mobile dunes continuously increased which show climate change in the area.

To further evaluate the results of land cover conversions, matrices of land cover changes from 1986 to 1989, 1989 to 1996, 1996 to 2001, and 2001 to 2009 were created (Table 3). In the table, unchanged pixels are located along the major diagonal of the matrix. Conversion values were sorted by area and listed in alphabetic order. These results indicate that increases in urban areas mainly came from conversion of agricultural and forest land to urban uses during the teen-year period from 1986 to 1996 and then again 2001 to 2009 (Table 3). In 1986 to 1989 4.48 Km^2 agriculture (2.08 Km^2) and forest (2.40 Km^2) area converted in urban and from 1989 to 1996 it was just double 8.38 Km^2 agriculture (3.87 Km^2) and forest (4.51 Km^2) area converted in urban area. After 1996 it increased slowly but from 2001 to 2009 agriculture area converted same speed but forest (14.74 Km^2) area is converted dramatically.

Table 3 shows that 7.03 Km^2 of forest was converted to urban between 1986 and 2009. These changes may seem to be classification errors, but forested areas are among some of the most sought after areas for developing new housing. Streets and highways were generally classified as urban, but when urban tree canopies along the streets grow and expand, the associated pixels may be classified as forest. We note that the changes from urban to forest occurred almost entirely near highways and streets. Classification errors may also cause other unusual changes. For example, between 1986 and 2009, 2.64 Km^2 of urban changed to agriculture and 2.32 Km^2 of urban and 10.86 Km^2 of agriculture changed to wetland. These changes are most likely associated with omission and commission errors in the Landsat classifications change map. Registration errors and edge effects can also cause apparent errors in the determination of change vs. no-change. Figure 2 shows the thematic land cover change images using the outputs of the supervised classification technique at two different dates. Table 3 shows the cross-tabulation matrix for the areas changed from one land cover class to another by percentage. The results show that the land cover change rate was very small, between 1986 and 1989. Forest and agriculture land occupied almost the maximum area 728.40 Km^2 (69.85%) with only very tiny spots of all remaining classes represented (30.15%). Between 1989 and 1996, the reclamation accelerated and the construction of new agrarian communities began. Consequently, new land cover classes were observed. Agriculture and forest land was transformed to urban land and water bodies, respectively.

Between 1996 and 2001, the whole infrastructure of the Apodi Valley region area was completed, therefore, impressive rates of change were observed. Around 43.81% of the land (other than forest and agriculture) in 1996 was developed to all other classes by 2001. Due to the remarkable change which occurred during this period, areas of no-change represented 87.02%, and the changed area represented 12.98%. From 2001 to 2009, changes in land cover also took place, but at a faster rate of change than 1996 to 2001. In 2009 shrimp farms,

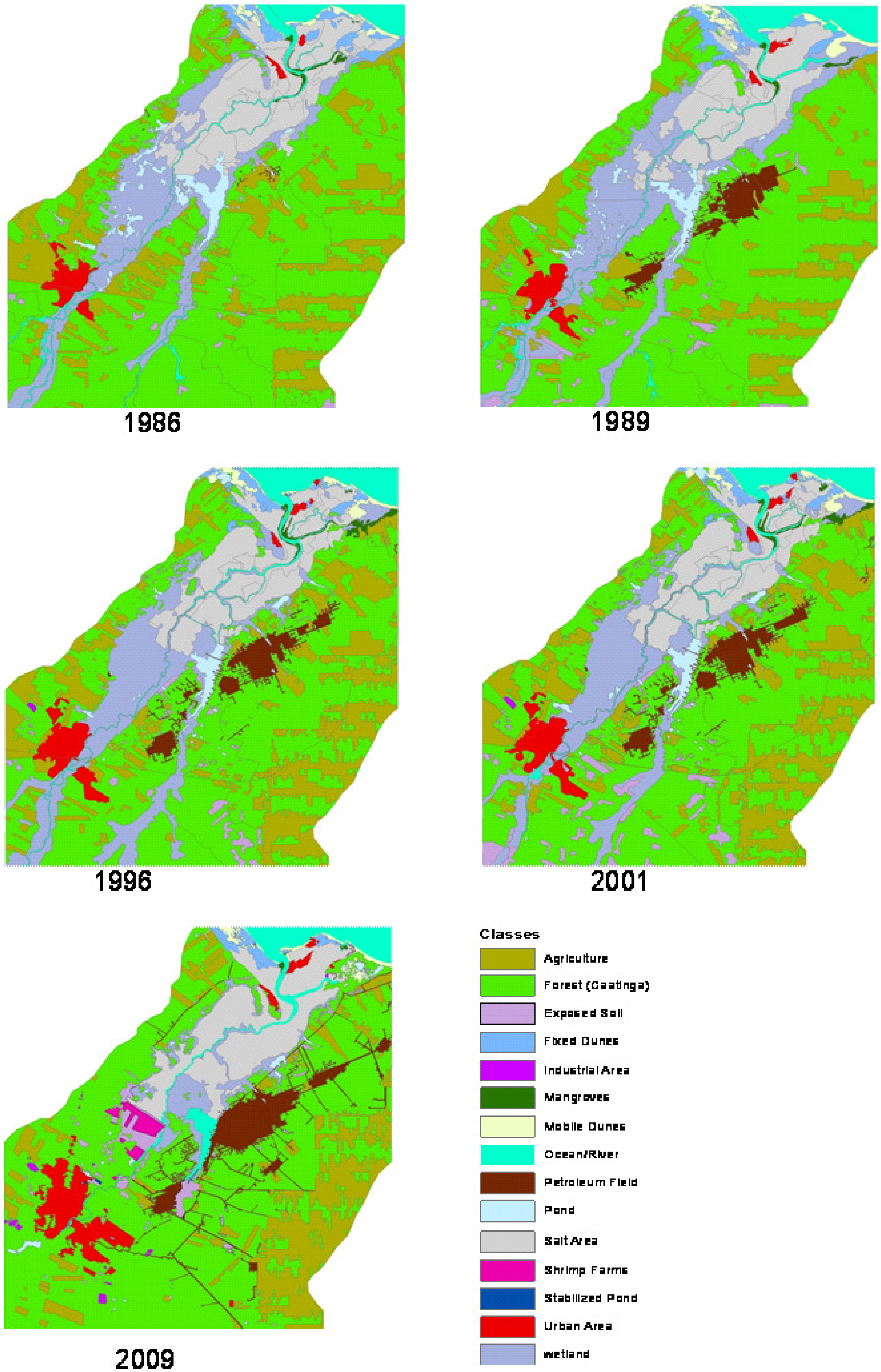

Figure 2. Thematic maps representing the spatial distribution of different land-cover classes, on different dates, within the Apodi Valley region, Northeast Brazil.

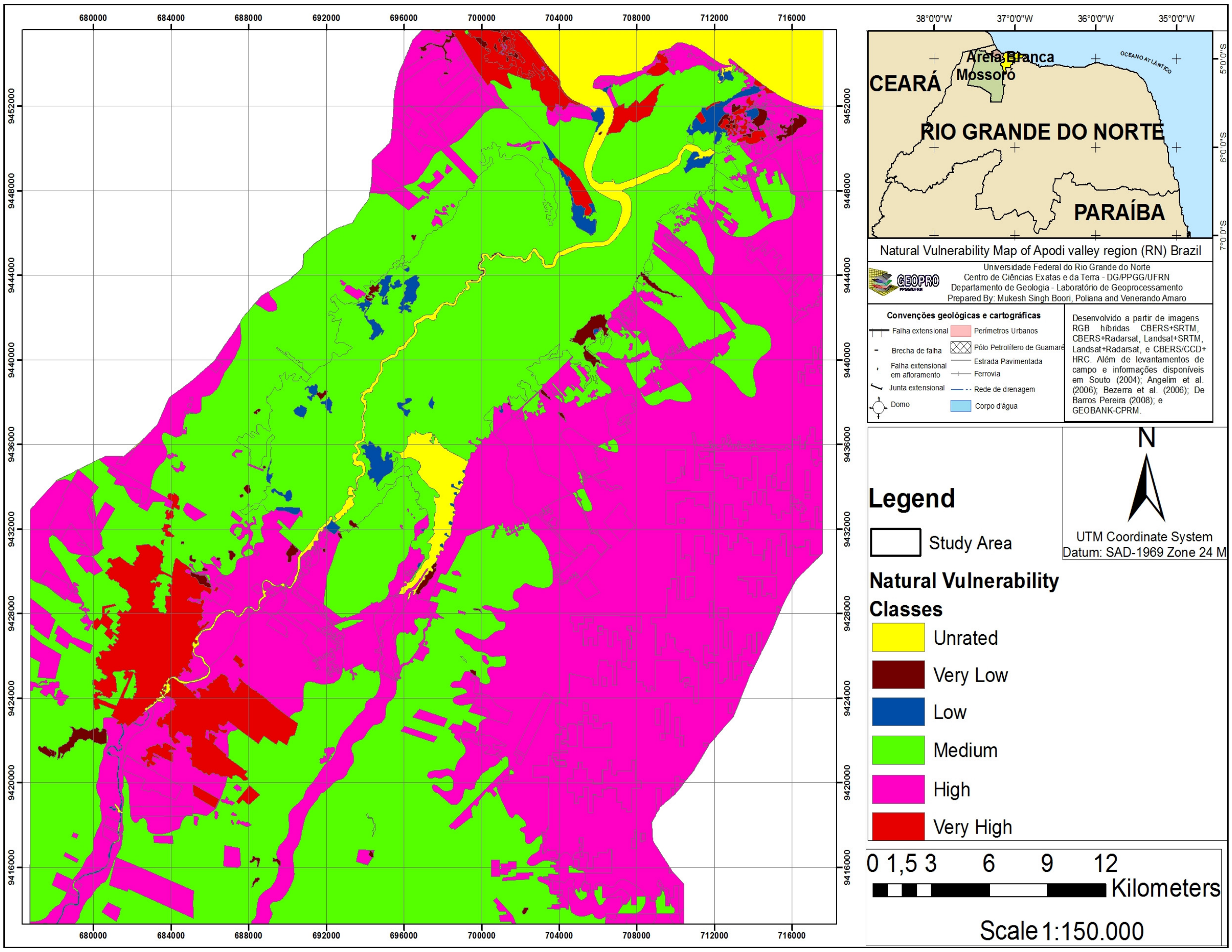

Figure 3. Natural vulnerability map of Apodi Valley region, Northeast Brazil.

Table 2. Summary of satellite classification area statistics for 1986, 1989, 1996, 2001 and 2009.

Class name	1986		1989		1996		2001		2009	
	(Km²)	(%)	(Km²)	(%)	(Km²)	(%)	(Km²)	(%)	(Km²)	(%)
Agriculture	234.20	17.05	192.57	14.03	244.62	19.58	242.33	17.84	189.51	13.8
Forest	692.93	50.46	677.33	49.37	623.85	49.92	616.46	45.40	724.29	52.76
Exposed soil	6.81	0.49	25.01	1.82	17.02	1.36	41.06	3.02	28.91	2.1
Fixed dunes	21.93	1.59	18.88	1.37	14.40	1.15	14.39	1.05	11.88	0.86
Industrial area	-	-	-	-	0.57	0.04	0.81	0.05	3.30	0.24
Mangroves	3.32	0.24	2.48	0.18	7.16	0.57	6.08	0.44	0.81	0.05
Mobile dunes	9.14	0.66	12.23	0.89	10.83	0.86	10.56	0.77	11.03	0.8
Ocean/river	53.34	3.88	53.61	3.90	49.43	3.95	48.55	3.57	66.98	4.87
Petroleum area	1.11	0.08	34.02	2.47	41.13	3.29	42.34	3.11	77.85	5.67
Ponds	30.47	2.21	23.93	1.74	17.75	1.42	19.73	1.45	8.93	0.65
Salt area	149.18	10.86	126.25	9.20	134.59	10.77	135.78	9.97	137.01	9.98
Shrimp farm	-	-	-	-	-	-	-	-	10.49	0.76
Stabilized pond	-	-	-	-	-	-	-	-	0.20	0.01
Urban area	18.74	1.36	22.88	1.66	29.94	2.39	31.30	2.30	53.30	3.88
Wetland	151.83	11.05	182.68	13.31	58.16	4.65	148.20	10.91	48.22	3.51
Total	1372.79	100	1372.79	100	1372.79	100	1372.79	100	1372.79	100

Table 3. Matrices of land cover and changes (Km²) from 1986 to 2009.

	Land cover														
	Agriculture	**Forest**	**Exposed soil**	**Fixed dunes**	**Industrial area**	**Mangro ves**	**Mobile dunes**	**Ocean/ river**	**Petroleum area**	**Ponds**	**Salt area**	**Shrimp farm**	**Stabilized pond**	**Urban area**	**Wetland**
1986								**1989**							
Agriculture	139.49	65.44	7.69	1.57	-	-	-	-	12.26	0.32	-	-	-	2.08	5.77
Forest	48.35	588.91	9.61	1.25	-	-	0.02	0.50	19.95	1.12	0.05	-	-	2.40	19.26
Exposed soil	0.66	2.08	3.39	-	-	-	-	0.37	0.10	-	-	-	-	-	-
Fixed dunes	0.21	0.26	0.02	12.50	-	0.56	2.21	0.10	-	0.82	1.22	-	-	0.61	3.73
Industrial area	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mangroves	-	-	-	0.02	-	0.98	-	0.82	-	-	0.88	-	-	-	0.66
Mobile dunes	-	0.05	-	1.52	-	-	6.11	0.56	-	0.34	0.53	-	-	-	0.02
Ocean/river	0.13	0.42	0.08	-	-	0.56	0.53	43.22	-	-	2.21	-	-	0.32	4.35
Petroleum area	-	0.42	0.02	-	-	-	-	-	0.34	0.08	-	-	-	-	-
Ponds	0.29	2.19	0.13	0.32	-	-	0.13	0.02	0.32	14.05	1.17	-	-	-	11.75
Salt area	-	0.53	-	0.82	-	0.24	3.47	3.92	-	0.66	114. 41	-	-	0.66	22.49
Shrimp farm	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Stabilized pond	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Urban area	1.14	0.61	-	-	-	-	-	0.05	-	-	0.37	-	-	16	0.72
Wetland	2.11	16.74	4.72	0.90	-	0.21	-	2.40	0.56	6.75	5.47	-	-	0.69	111.84
1989								**1996**							
Agriculture	135.62	47.36	1.06	-	-	0.13	-	0.02	0.48	0.34	-	-	-	3.87	2.67
Forest	94.67	522.74	10.89	0.93	-	0.02	0.37	0.02	15.27	1.57	0.32	-	-	4.51	26.52
Exposed soil	6.51	10.63	2.32	0.02	-	-	-	0.05	0.42	0.10	-	-	-	-	4.94
Fixed dunes	0.88	3.60	-	9.61	-	0.88	1.38	0.02	-	1.14	0.77	-	-	0.26	0.29
Industrial area	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mangroves	-	-	-	0.05	-	1.49	-	0.48	-	-	0.02	-	-	-	0.48
Mobile dunes	-	0.10	-	1.70	-	-	7.93	1.14	-	0.02	0.98	-	-	-	0.40
Ocean/river	0.21	0.29	-	0.13	-	0.85	0.40	40.47	-	0.24	2.43	-	-	0.05	7.66
Petroleum area	0.80	8.20	0.02	-	-	-	-	-	23.85	0.37	-	-	-	-	0.13

Table 3. Contd.

Ponds	-	1.92	0.02	0.50	-	-	0.40	0.18	0.48	9.34	3.25	-	-	-	7.72
Salt area	-	1.30	-	0.58	-	1.60	-	2.93	-	0.08	110.99	-	-	0.40	7.93
Shrimp farm	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Stabilized pond	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Urban area	0.34	0.34	-	0.21	-	-	-	0.26	-	-	0.10	-	-	20.16	1.54
Wetland	5.39	28.66	2.16	0.61	-	2.51	0.18	2.85	0.29	4.78	15.62	-	-	0.32	117.75
1996								**2001**							
Agriculture	202.37	29.73	8.33	-	-	0.08	-	-	1.09	0.08	-	-	-	0.66	0.69
Forest	31.41	559.69	9.88	0.80	0.18	-	0.02	0.13	7.21	1.52	0.66	-	-	0.98	8.01
Exposed soil	2.40	1.04	12.98	-	-	-	-	-	-	0.02	-	-	-	-	-
Fixed dunes	-	0.69	-	11.56	-	0.02	0.88	-	-	0.10	0.69	-	-	0.18	0.21
Industrial area	-	-	-	-	0.61	-	-	-	-	-	-	-	-	-	-
Mangroves	0.77	0.88	-	0.05	-	4.06	-	0.77	-	0.05	0.61	-	-	-	0.29
Mobile dunes	-	-	-	1.06	-	-	8.81	0.32	-	0.08	0.10	-	-	0.02	0.24
Ocean/river	0.05	0.10	0.02	0.08	-	0.34	0.40	42.66	-	-	1.38	-	-	0.24	2.61
Petroleum area	0.48	5.63	-	-	-	-	-	-	33.47	0.16	-	-	-	-	0.08
Ponds	0.13	1.04	0.02	0.08	-	0.02	0.08	0.02	0.18	14.87	0.24	-	-	-	0.90
Salt area	-	0.72	-	0.53	-	1.04	0.34	0.74	-	0.08	128.64	-	-	0.16	1.68
Shrimp farm	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Stabilized pond	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Urban area	0.16	0.64	-	0.05	-	-	-	-	-	0.02	0.05	-	-	27.86	0.66
Wetland	4.06	17.20	9.75	0.05	-	0.37	0.10	2.93	0.13	2.16	3.63	-	-	1.12	132.87
2001								**2009**							
Agriculture	91.99	129.31	3.09	0.45	0.02	-	0.29	0.24	7.96	1.20	1.09	-	-	3.65	1.73
Forest	91.17	444.71	6.57	0.61	2.24	0.08	0.53	1.84	36.67	2.96	6.70	0.08	-	14.74	9.24
Exposed soil	1.54	33.33	0.45	-	0.64	-	-	0.34	0.96	0.05	0.02	-	-	2.03	1.70
Fixed dunes	0.02	1.86	0.16	3.68	-	0.02	2.35	2.64	0.08	0.18	2.93	-	-	0.21	0.10
Industrial area	0.05	0.50	0.08	-	0.18	-	-	-	-	-	-	-	-	-	-
Mangroves	-	1.06	0.02	0.05	-	0.08	1.14	1.57	-	0.16	1.78	-	-	-	-
Mobile dunes	0.08	1.36	0.13	1.70	-	-	2.32	4.00	-	1.04	0.02	-	-	-	-
Ocean/river	0.05	1.65	0.32	0.13	-	0.40	0.21	36.43	0.02	0.02	5.82	0.32	0.08	1.06	0.40
Petroleum area	1.28	12.12	0.10	-	-	-	-	0.53	27.96	0.13	0.24	-	-	-	0.37
Ponds	0.16	3.92	0.45	0.93	-	-	0.82	6.27	0.88	0.18	2.77	0.45	-	0.05	2.83

Table 3. Contd.

Salt area	0.18	8.20	0.53	4.08	0.02	0.26	1.89	7.31	-	0.18	94.21	-	-	2.51	16.53
Shrimp farm	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Stabilized pond	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Urban area	-	5.44	0.13	-	-	-	0.26	0.64	-	-	1.49	-	-	23.32	-
Wetland	1.65	74.12	16.48	0.32	0.21	-	1.25	3.41	1.46	2.67	18.19	9.10	0.10	5.07	14.37

stabilized pond comes as a new classes and land degradation was increase.

The unchanged area represented 56.06% (729.24 Km²) and 43.93% (643.55 Km²) of the area was changed (Table 3).

The nature of the changes of different land cover classes could be derived from Table 3, e.g. forest area covered 616.41 Km^2 in 2001 and 724.29 Km^2 in 2009. Out of the 725 Km² that was cropland in 1986, 444.71 Km² still forest land in 2009 but 91.17 Km^2 was converted to agriculture land by the local peoples, 36.67 Km² was converted to petroleum area, 9.24 Km² was converted in wetland and 14.74 Km² was converted to urban. At the same time, the increase of forest area, from 2001 to 2009, was 129.31 Km^2 from agriculture, 33.33 from exposed soil land.

Agriculture covered an area of 242.33 Km² in 2001 and 189.51 Km² in 2009. It might seem from these figure that 53.82 Km² was degraded but through cross-tabulation analysis 129.31 Km^2 out of the lost agriculture was converted to forest land which is a positive change and not land degradation, only 19.72 Km² (converted to other than forest class) was degra-ded. At the same time, 48.03 Km^2 from agriculture forest, exposed soil, fixed dunes and wetland was converted to petroleum area. This explains the importance of integrating remote sensing and GIS in the study of land cover change detection since it provides essential information about the nature and spatial distribution of land cover changes. We have to take into consideration the accuracy of the classifi-cation of different classes since the error of the classification will be affect the accuracy of the change detection figures.

Land degradation processes in the study area are; degradation of natural vegetation due to overgrazing and the remarkable inter-annual variation in the amount of rainfall. Water logging which results from mismanage-ment of irrigation is another cause of land degradation. The main problems associated with irrigation schemes are their wasteful use of water, with application rates exceeding possible plant uptake as well as poor drainage system and leading to problems associated with water logging; salinization and alkalinization. This could be seen on the land cover/land use map of 2009. The third land degradation process in the study area is wind erosion and water erosion, which accelerate as a result of the loss of vegetation cover. Wind and water erosion led to the removal of the relatively fertile topsoil and this could lead to desertification.

RESULTS AND DISCUSSION

Natural and environmental vulnerability maps is an effective relationship between ecosystem, land use and vulnerability and making comparisons between ecosystem, service sectors, scenarios and regions to tackle questions such as: Which regions are most vulnerable to change? How do the vulnerabilities of two regions compare? Which sectors are the most vulnerable in a certain region? Which scenario is the least harmful for a sector? How, where, why and in which direction vulnerability goes?

Natural vulnerability map

Figure 4 shows the natural vulnerability in the study area. The total area of the study is 1372.79 Km^2. The values found in the natural vulnerability map reflect the suscep-tibility of the environment because the stability conditions of the morpho-pedogenesis of the area. The area of natural vulnerability corresponds to very high and high in river plains, tropical fruit agriculture part, oil and natural gas exploration fields, mangrove, dune fields, beach and urban area. An area of 597.65 km^2, accounting for 43.49% of the total area of the Apodi Valley region, belongs to the high vulnerable zone, and 4.94% to the very high vulnerable zone in the Valley. This means that near to half (665.63 km^2, 48.43%) of the total area of the Apodi Valley region was very vulnerable and show a high sensitive zone, so policy makers must be calculate it for future land use scenario/policies. The medium and the low

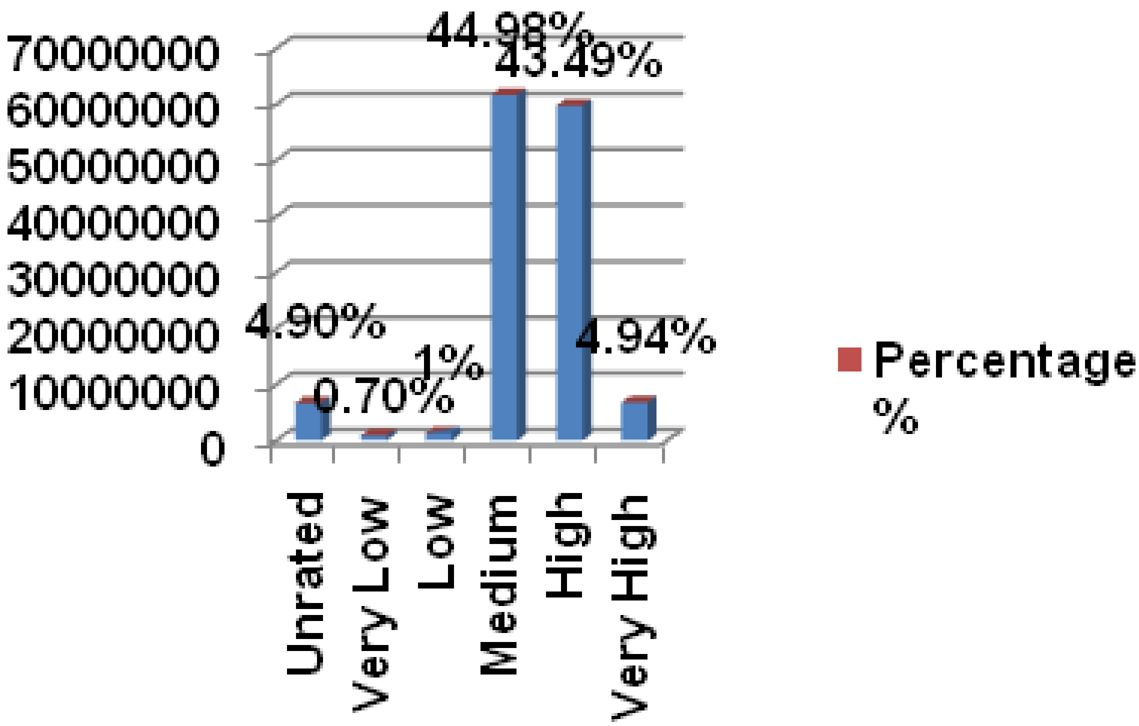

Figure 4. Natural Vulnerability Graph of the Apodi Valley Region- RN, Brazil.

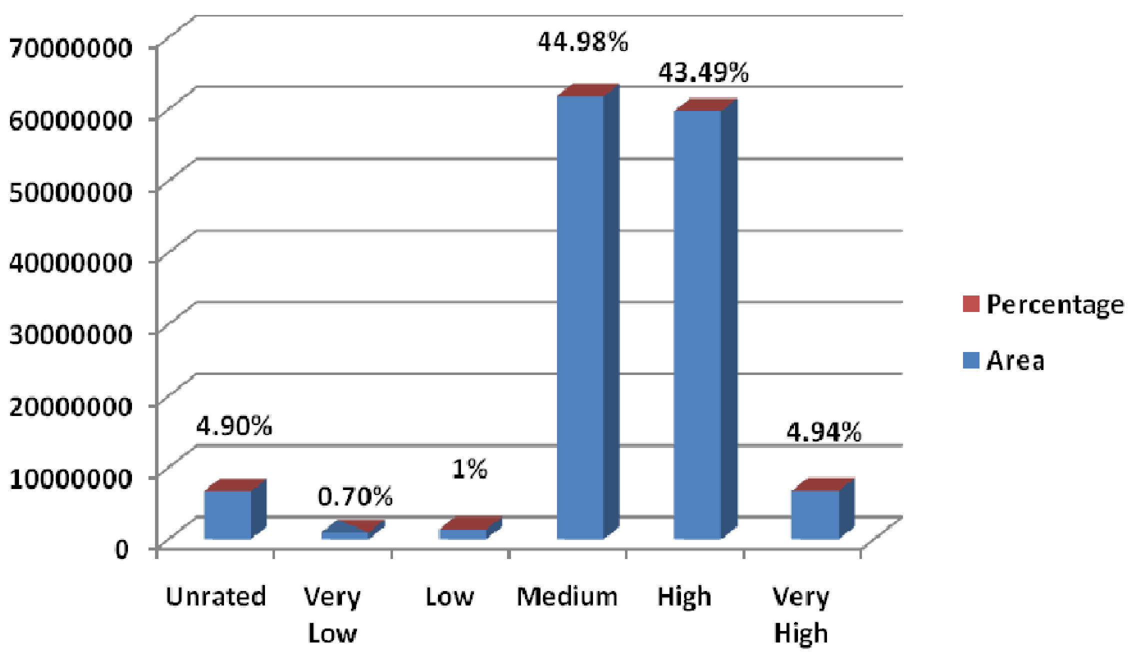

Figure 5. Natural vulnerability graph of the Apodi Valley region- RN, Brazil Environmental Vulnerability Map

vulnerable zone accounted for 44.98% (618.03 km^2) and 1.0% (13.75 km^2) and is present in caating forest, agriculture land, salt and shrimp farm respectively, whereas the very low and unrated vulnerable zone has only a small proportion of 5.60% (77.06 km^2) (Figure 4). The profile of the Apodi Valley region natural vulnerability showed an asymmetry normal distribution but the center of the profile lean to the 'high' level (Figure 5).

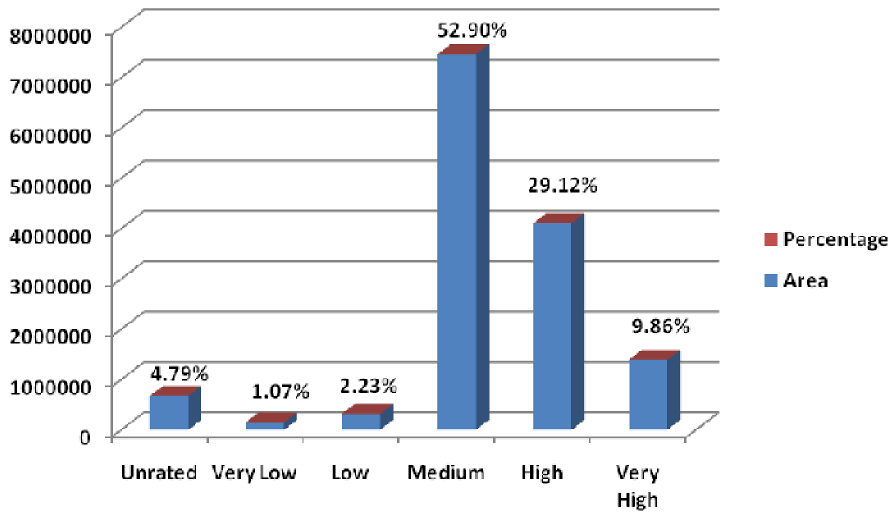

Figure 6. Environmental vulnerability graph of the Apodi Valley Region- RN, Brazil.

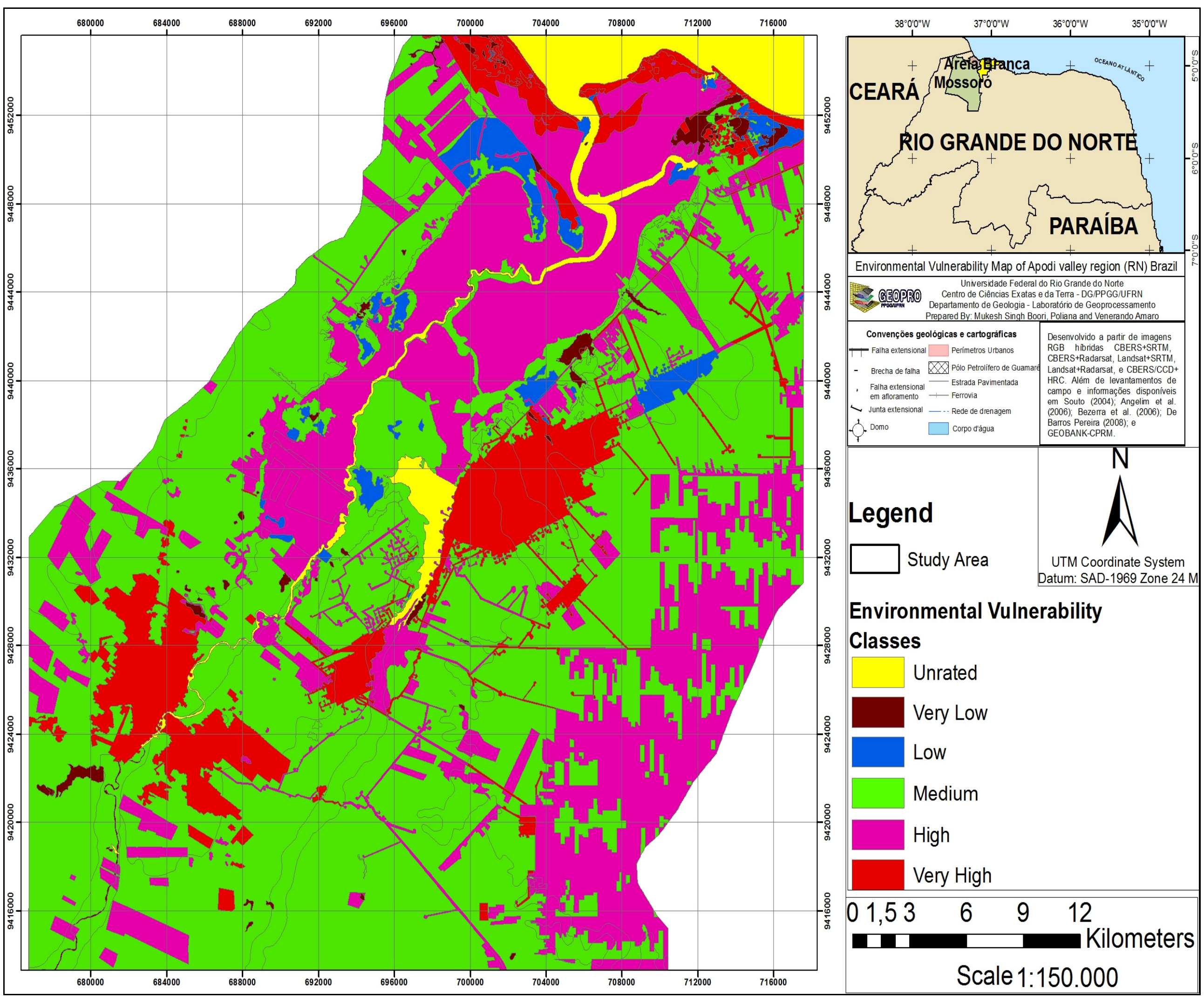

Figure 7. Environmental vulnerability map of Apodi Valley region, RN- Brazil.

Environmental vulnerability map

The evaluated results for environmental vulnerability are shown in Figure 6. Overall regions with potential/unrated, very low and low status were made up 8.09% (114.41 km²) of the total area of the Apodi valley region, indicating moderate overall integrated environmental vulnerability. An area of 410.62 km², accounting for 29.12% of the total area of Apodi valley region, was classified as having high vulnerability, and 139.10 km² (9.86%) as very high vulnerability. Thus one sixth of the total area of the Apodi valley region was very vulnerable. The medium vulnerable area made up 52.90% (745.96 km²), and low vulnerability area was 2.23% (31.58 km²), whilst the area of very low vulnerability and potential vulnerability accounted for 1.07% (15.20 km²) and 4.79% (67.61 km²), respectively. In general, the environmental vulnerability of the Apodi Valley region exhibited an asymmetrical normal distribution centered on a 'high' vulnerability level.

From the map of integrated environmental vulnerability (Figure 7), the areas with potential, very low and low environmental vulnerability were located in three regions: caatinga forest, ocean/river and fixed vegetation area. In the mid part of the Apodi Valley region low levels of environmental vulnerability were due to the higher vegetation condition and lower intensity of human activities. However, blocks with high or very high environmental vulnerability were visible within these areas, due to urbanization, industrial activities (shrimp farms, salt industry, oil and natural gas exploration), and steep slopes resulting in less forest protection, serious soil erosion and high rate exploration of natural resources. It was notable that the environmental vulnerability in the areas immediately surrounding Apodi River or costal area was most frequently potential to low, with only a few areas with high or very high vulnerability. Whilst better vegetation conditions and lower levels of anthropogenic interference were again factors underlying this pattern, the relatively low hypsography and the microclimate around the river were also important in providing better water heat conditions.

Three regions with very high vulnerability were located in Apodi valley region were urban area/city, centre part of valley and costal area special beach area. These areas were urban, industrial and most socio-economic activity sites with high densities of buildings and limited vegetation cover, bad geological conditions or high exploration of natural resources, which increased the environmental vulnerability. Areas with higher vulnerability were generally distributed in the north to centre and east part. Most areas with medium vulnerability, where eco-environment and human activity intensity were moderate, were located in the Basin of Apodi River and the southern part of the Valley. These are marine salt pond and agricultural areas with the main land use type being paddy fields and dry land, along with some grassland and woodland. The environment of these areas was affected mostly by human activity.

Application in vulnerability management

Environmental and ecosystem vulnerability assessment may be a valuable tool in area of vulnerability management, and a complex system of effect that produces the actual quality of an exposed community or ecosystem. Therefore, the vulnerability assessment supports sensitivity management in better defining the target of protection and in developing scenarios of potential impact based on a number of environmental traits. Environmental and ecosystem vulnerability assessment may be expressed with a score or level of potential impact related to a certain stressor in a given environment. Furthermore, the actual status of a polluted ecosystem or community represents the response of a (more or less) pristine ecosystem or community to a specific stressor or to multiple stressors. Combining the assessment of vulnerability of a pristine ecosystem or community with the actual status allows obtaining crucial information for vulnerability management, with which two different objectives can be met: (1) Qualitative restoration of impacted ecosystems, and (2) Protection of natural and high quality ecosystems against potential impact. Vulnerability managers may also consider several potential scenarios of impact related to single or multiple stressors. In the first case, a ranking of substances related to vulnerability of a real ecosystem or community may be performed and could be site-specific and species-specific. In the second case, vulnerability managers may predict the impact on a pristine ecosystem considering how a certain community or ecosystem reacts to multiple stressors, and also may identify hot spots. This is the case, for example, of aquatic ecosystems where urban, industrial and agricultural stressors may be contemporarily present. The actual status represents the result of the vulnerability of the pristine ecosystem to those multiple stressors. Comparing the actual status with a pristine reference community may give indications on which populations are more endangered, on which ecosystem service is more vulnerable, on which kind of adaptive capacity could be developed by a community or an ecosystem (Jensen, 2004). In this perspective, environmental vulnerability assessment could be recognized as a valuable tool in bio-hydro-geo-morphological diversity vulnerability management, and could provide relevant knowledge in supporting bio-hydro-geo-morphological diversity policies development and related action to prevent a further loss as required by the government. As we previously mentioned, the vulnerability assessment represents a tool for assessing how to manage the transition to a better quality of the exposed ecosystem, to assess the naturalistic value of the exposed ecosystem, to integrate a socio-economic value; basically considering ecosystem services provided by the exposed ecosystem.

Sensitivity assessment to vulnerability assessment

As shown here in this review, the concept of environmental vulnerability has gained increasing interest in ecosystem sensitivity assessment. What are the perspec-tives for future development of vulnerability analysis for environmental sensitivity assessment? When the objec-tive of sensitivity assessment is to describe specific environments or to assess environmental quality or the sensitivity for specific ecosystems, an analysis based on sensitivity will not suffice entirely. In those cases, a vulnerability analysis, including the biology of the receiving biota describing susceptibility to exposure and population recovery, is more appropriate. For a site-specific assessment, the characteristics of the endangered hydro-geological and biological community (structure, sensitivity, vulnerability, naturalistic value, etc.) are then needed.

Thus, there is a need for environmental or ecosystem vulnerability analysis. Currently, most methods described in this review are qualitative assessments of vulnerability. This is valuable for comparing hazards; the current methods provide good starting points to do so. There are two areas where the methodology can be improved, and where our framework may be a helpful guiding tool. First, the current methodology for assessing vulnerability at ecosystem level needs to be further developed and improved. The methods described by De Lange et al. (2009) for species vulnerability and Halpern et al. (2007) for marine ecosystems give a good starting point to work from. Second, there is a need for quantitative vulnerability results. How to quantify vulnerability will be one of the major research issues for the coming years. This is not an easy task; vulnerability is not easily reduced to a single metric and is not easily quantifiable (Adger, 2006). Still, difficult tasks can be accomplished. An approach including measurements *in situ* on populations, commu-nities and ecosystems, combined with quantification of the stressor, will be essential. Further, once a form of vulnerability measure is obtained, there is a need to establish some threshold of sensitivity, danger or harm (Adger, 2006). Implementation of environmental vulnera-bility assessment may be best accomplished by using a tiered approach, with increasing level of detail at higher tiers.

The recent paper by Baird et al. (2008) states that using traits in environmental vulnerability assessment can be regarded as the new frontier in this field of science. Assessing environmental vulnerability by using hydro-geological and ecological information on different hierarchical levels, as proposed in this paper, is in our opinion a valuable contribution to this since long advocated plea for more ecology in Apodi Valley region.

Conclusions

Hydro-geophysical parameter and land use change will have a large influence on important ecosystem in Apodi Valley region. Vulnerability to land use change differs across study region. While projected land use changes can be negative for one sector, other sectors could benefit. There are differences in potential impact for the different scenarios in most regions, with the most notable distinctions caused by differences in economic versus environmentally oriented development. These differences are most profound in socio-economic sites, such as agricultural, industrial and urbanization. While the ability to cope with such negative impacts increases with growing economic development, Apodi region is projected to have a considerably lower adaptive capacity than other parts. From this, it can be concluded that the agricultural and industrial sectors will be most vulnerable to projected land use changes in Apodi Valley region. Analysis shows the pattern indexes may give a good indication for the vulnerability of regional eco-environment on the whole, but several indexes are poor indicators. So selecting the pattern indices of landscape for vulnerability analysis of regional eco-environment is still needed to be investigated further. In addition, the integrated information of the pattern indexes also has a good indication for the interior relationships between the pattern indexes and the driving factors of regional eco-environment vulnerability, but interaction mechanisms within the driving factors of vulnerability, together with the integrated impact mechanisms that driving factors act on regional ecological vulnerability, still remains to further study. However, the differences in both potential impacts and adaptive capacity, shows that the vulnerably of Apodi Valley region is strongly influenced by different develop-ment pathways. Society and policy will therefore play an important role in determining the eventual, residual impacts.

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