NILSON CLEMENTINO FERREIRA

MODELO CONCEITUAL, LÓGICO E FÍSICO DE UM SISTEMA PARA O MONITORAMENTO INTEGRADO E SISTEMÁTICO DA FLORESTA AMAZÔNICA A PARTIR DA ANÁLISE DE PRODUTOS DE SENSORIAMENTO REMOTO, DADOS CENSITÁRIOS E CARTOGRÁFICOS.

Tese de Doutorado Apresentada ao Programa de Doutorado em Ciências Ambientais para Obtenção do Título de Doutor em Ciências Ambientais

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CANDIDATO: NILSON CLEMENTINO FERREIRA

ORIENTADOR: PROF. DR. LAERTE GUIMARÃES FERREIRA JR.

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Prof. Dr. Laerte Guimarães Ferreira - UFG

Prof. Dr. Fausto Miziara - UFG

Prof. Dr. José Alexandre Felizola Diniz Filho - UFG

Profa. Dra. Mercedes Maria da Cunha Bustamante - UnB

Prof. Dr. Edson Eijy Sano – Embrapa Cerrados

Dedicatória

Aos meus pais Ely e Odete pelo amor, apoio e orientação durante toda minha vida.

À minha esposa Noely e ao meu filho Leonardo, pelo imenso amor, suporte, companheirismo e compreensão durante toda esta jornada.

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RESUMO

A região Amazônica, dada as suas dimensões territoriais, quantidade de rios, clima úmido e cobertura florestal, é de extrema importância para o equilíbrio climático regional e global. Porém, a disponibilidade de riquezas naturais e principalmente de terras para a implantação de agricultura e pecuária, vem atraindo desde a década de 1970 inúmeras ações que causam a derrubada de extensas áreas cobertas por floresta. Em fato, estima-se que aproximadamente 17.800 km^2 de florestas sejam desmatados anualmente, em função de alterações no contexto sócio-econômico e político-institucional, bem como da falta de programas de gestão territorial para a região.

Através dos produtos e técnicas de sensoriamento remoto, estes desmatamentos vêm sendo acompanhados anualmente desde 1987. Por outro lado, o recente desenvolvimento de sensores orbitais para monitoramento global, com altas resoluções temporais e resoluções espaciais moderadas, além de melhores resoluções espectrais e radiométricas, tem possibilitado monitorar os desmatamentos em curso de forma mais sistemática, precisa e freqüente. Dentre estes novos sensores, destaca-se o MODIS (MODerate Imaging Spectroradiometer), carro chefe do programa Sistema de Observação Terrestre (EOS – NASA), cujos dados, corrigidos para efeitos atmosféricos e georeferenciados, são distribuídos gratuitamente na forma de diferentes produtos. Para o monitoramento da cobertura vegetal em particular, foi desenvolvido o produto MOD13 (índices de vegetação), produzidos a cada 16 dias com resoluções de 250, 500 e 1000m.

Tendo por base o produto MOD13Q1 (250m de resolução espacial) e especificamente o índice de vegetação da diferença normalizada (NDVI), foi elaborada no âmbito desta tese de doutoramento a modelagem conceitual, lógica e física de um sistema aplicado ao monitoramento de toda a área geográfica coberta pela floresta amazônica no Brasil, cerca de 3.5 milhões de quilômetros quadrados. Em função da plataforma de desenvolvimento, um Sistema de Informações Geográficas (SIG), o sistema de monitoramento integra dados sociais, econômicos e institucionais com dados de desmatamentos oriundos de sensoriamento remoto, fornecendo assim informações geograficamente referenciadas a respeito das causas, efeitos e tendências dos desmatamentos na Amazônia brasileira. A partir dos dados de desmatamentos obtidos através deste sistema, bem como através de outras iniciativas de monitoramento, como por exemplo dados fornecidos pelo Programa de Monitoramento do Desflorestamento (PRODES / INPE), foi também possível entender e modelar a relação entre desmatamento e estrutura fundiária na Amazônia. Ainda no âmbito desta tese, avaliamos os impactos dos desmatamentos sobre a paisagem, bem como a resposta dos índices de vegetação MODIS à fragmentação dos remanescentes florestais.

ABSTRACT

The Amazon region, due to its territorial dimension, large number of rivers, humid climate, and extensive vegetative cover, plays an instrumental role for the regional and global climatic balance. However, abundant natural resources, and in particular, the availability of land for agriculture and cattle ranching, have motivated, since the early 1970's, many occupation initiatives and a severe clear cutting of extensive forested areas. In fact, it is estimated that approximately 17.800 km^2 of pristine forests are converted each year, driven by changes in the social, economical, political, and institutional context, as well as due to the lack of territorial policies for the region. With the help of remote sensing technology, these deforestations have been closely monitored since 1987. On the other hand, the recent development of new orbital sensors for global biosphere observations, with high temporal resolutions and moderate spatial resolutions, besides improved spectral and radiometric responses, have made possible the systematic mapping of ongoing deforestations in a more precise and frequent manner. Among these new sensors, it should be emphasized the MODIS (MODerate Imaging Spectroradiometer), flagship of the Earth Observation System (EOS – NASA), whose data, corrected for atmospheric effects and geocoded, are made available, at no cost, in the form of different standard products. In particular, for the monitoring of the vegetation cover, regarding its temporal and spatial dynamics, there is the product MOD13 (vegetation index), produced at every 16 days, with spatial resolutions of 250, 500, and 1000m. Based on the

MOD13Q1 product (250m spatial resolution) and its normalized difference vegetation index (NDVI), it was elaborated, within the scope of this PhD dissertation, the conceptual, physical, and logical model of a warning deforestation system for the entire geographical forest area (about 3.5 million km^2) of the Brazilian Amazon. Considering the development platform, a Geographical Information System (GIS), this monitoring system is able to integrate both census (i.e. economical, social, and institutional) and remote sensing derived deforestation data. In this way, it is possible to provide geographically referenced data on the causes, effects and trends of the deforestations in the Brazilian Amazon. Based on the deforestation information obtained via this system, as well as from other monitoring initiatives, like the data provided by the Deforestation Monitoring Program (PRODES / INPE), it was also possible to understand and model the correlation between deforestation and the land tenure structure in the Amazon. Finally, in this dissertation work we also attempted to quantitatively assess the impacts of deforestation over the Amazon landscapes and the response of the MODIS vegetation indices to the remnants fragments.

INTRODUÇÃO

A floresta amazônica ocupa uma área de aproximadamente 3,5 milhões de quilômetros quadrados em território Brasileiro. A imensa quantidade de rios e o clima extremamente úmido e quente proporcionam a manutenção de uma extensa e densa floresta, de grande importância para o equilíbrio climático regional e possivelmente global.

A partir de 1970, em função de programas governamentais para ocupação e uso daquela região, através dos quais foram implantadas várias obras de infra-estrutura, bem como facilidades para obtenção de créditos, diversas áreas da floresta amazônica começaram a serem convertidas em agricultura e pecuária. Por outro lado, e apesar dos incentivos fiscais e financeiros terem sido reduzidos, as derrubadas de florestas não diminuíram. Ao contrário, dados de diversos programas de monitoramento (ex. PRODES, 2000) mostram que a taxa de incremento dos desmatamentos vem aumentando ano a ano, situando-se atualmente em cerca de 17.800 km^2 anuais.

O monitoramento dos desmatamentos ocorridos na floresta amazônica vem sendo realizado de forma sistemática desde 1987, a partir da interpretação de imagens Landsat 5 – TM e Landsat 7 – ETM+. Ainda que estas imagens apresentem resolução temporal nominal de 16 dias, os custos financeiros para obtenção, processamento e interpretação dessas imagens, bem como a grande ocorrência de nuvens sobre a região Amazônica, fazem com que este mapeamento seja anual.

Por outro lado, e considerando a acentuada dinâmica espaço-temporal do uso e ocupação da terra em grande parte da Amazônia, um sistema para monitoramento sistemático e efetivo das áreas de floresta deve ser capaz de fornecer informações mais rápidas, simplificadas e freqüentes. Além disso, o sistema deve possibilitar, da forma mais automatizada quanto possível, a análise dos dados de desmatamentos em relação às variáveis sociais, econômicas e institucionais que induzem inicialmente a ocupação e/ou apropriação de terras e, em um segundo momento, os desmatamentos. Da mesma forma, o sistema deve ser capaz de avaliar os impactos ecológicos dos desmatamentos, uma vez que atualmente as preocupações tem sido preferencialmente focadas nas taxas anuais de incrementos dos desmatamentos ocorridos, sem maiores preocupações com a qualidade dos fragmentos de florestas remanescentes.

Neste sentido, e tendo por base o pressuposto de que tão importante quanto mapear os desmatamentos em curso é entender as suas causas, impactos e tendências, esta tese propõe uma nova abordagem para o monitoramento integrado da floresta Amazônica, cujo resultado direto é o Sistema Integrado de Alerta de Desmatamentos para a Amazônia Legal (SIAD – AM), objeto de convênio estabelecido entre a Universidade Federal de Goiás (UFG) e o Sistema de Proteção da Amazônia (SIPAM) no período de maio de 2004 a janeiro de 2006.

Em função da plataforma de desenvolvimento escolhida, um Sistema de Informações Geográficas (SIG), o sistema em questão, totalmente operacional, possibilita realizar a integração de dados oriundos do sensoriamento remoto, utilizados para o mapeamento de desmatamentos, com dados sociais, econômicos, institucionais, cartográficos e temáticos.

Especificamente para a detecção e mapeamento dos desmatamentos, e tendo em vista um processo automatizado, de baixo custo e com alta freqüência, avaliamos no âmbito desta tese as imagens índices de vegetação com 250m de resolução espacial do sensor MODIS (MODerate Resolution Imaging Spectroradiometer). Estas imagens, conhecidas como produto MOD13Q1, são disponibilizadas a cada 16 dias em formato georeferenciado e acompanhadas de uma série de imagens acessórias, entre as quais as imagens *quality assurance*, um conjunto de metadados que descreve *pixel* a *pixel* a qualidade dos índices de vegetação e dos dados de reflectância utilizados.

O desenvolvimento desta tese de doutoramento situa-se em torno de três questões principais, as quais procuramos responder ao longo dos capítulos que se seguem: a-) qual seria a abordagem metodológica para se mapear automaticamente desmatamentos a partir do produto MOD13Q1 em um ambiente SIG e qual é a precisão e limitações deste mapeamento; b-) É possível modelar a ocorrência de desmatamentos a partir do seu contexto sócio-econômico e institucional com vistas à identificação de áreas críticas de desmatamentos, bem como a determinação de tendências futuras?; e c-) Qual o impacto da fragmentação da paisagem sobre os remanescentes de florestas, e como os índices de vegetação MODIS respondem à estes impactos?

Para responder essas questões, foram elaboradas as seguintes abordagens:

1 – Para o mapeamento automatizado dos **desmatamentos**, a análise comparativa de imagens **índices de vegetação** do produto MOD13Q1 foi precedida pela análise das respectivas imagens de qualidade (i.e. metadados), com vistas a serem eliminados *pixels* contaminados por nuvem, sombra, aerossol, etc, os quais são os principais responsáveis pelos erros de comissão (i.e. falsos desmatamentos). Da mesma forma, para a análise da diferença de duas imagens índices de vegetação consecutivas considerou-se o **contexto geográfico** das mesmas, haja vista a maior incidência de desmatamentos junto a estradas, etc.

2 – Com vistas ao entendimento sobre as causas dos desmatamentos, buscou-se nas ciências sociais os modelos teóricos que explicam a **ocupação, apropriação e usos do solo**. Uma vez identificadas as variáveis sociais e econômicas que satisfazem os modelos teóricos em questão, utilizaram-se técnicas estatísticas a fim de se obter a relação entre tais variáveis com os desmatamentos. Através da utilização de **estatística espacial** foi possível elaborar o mapeamento das áreas críticas de desmatamentos.

3 – Com o intuito de se avaliar a influência da fragmentação sobre as áreas de **florestas remanescentes**, utilizou-se técnicas da **ecologia de paisagem**, bem como modelos estatísticos com ajustes gerais e locais, para se quantificar os **distúrbios da paisagem**, bem como a influência destes sobre os índices de vegetação.

ESTRUTURA DA TESE

O corpo principal desta tese é composto por três artigos científicos, inseridos como apêndices. Os mapeamentos automatizados de desmatamentos, tendo por base a comparação de imagens do produto MOD13Q1 em um ambiente SIG, avaliam a diminuição do índice de vegetação *pixel* a *pixel*, considerando o seu contexto geográfico, conforme está descrito no apêndice 1.

Por outro lado, a quantificação dos desmatamentos em relação aos municípios, unidades de conservação ou ainda em relação à tipologia vegetal fornece apenas um conhecimento empírico a respeito da realidade local. Assim, faz-se necessário investigar cientificamente as variáveis sociais e econômicas que induzem o desmatamento. Os modelos teóricos que explicam a ocupação, apropriação e uso do solo foram imprescindíveis na seleção das variáveis sociais e econômicas indutoras de desmatamentos, avaliadas em ambientes SIG através do uso de estatística espacial para se mapear áreas críticas de desmatamentos, conforme descrito no apêndice 2.

Finalmente, no apêndice 3 são analisados os impactos dos desmatamentos ocorridos ao longo das últimas décadas sobre os remanescentes florestais. Em particular, o estudo apresentado neste apêndice avalia, com base em modelos estatísticos que levam em conta a distribuição geográfica das variáveis, como os índices de vegetação MODIS respondem a estes distúrbios à escala da paisagem.

No primeiro artigo, aceito para publicação no International Journal of Remote Sensing, o autor, sob a orientação do Prof. Dr. Laerte Guimarães

Ferreira Jr., desenvolveu os métodos de análises temporal dos índices de vegetação de produtos MOD13Q1, considerando tanto as informações contidas nos metadados, quanto o contexto espacial de cada *pixel* de imagem. Também colaboraram com este artigo, o Dr. Alfredo Huete do *Terrestrial Biophysics and Remote Sensing Lab* (*University of Arizona*), e o *M.Sc.* Manuel Eduardo Ferreira, do Laboratório de Processamento de Imagens e Geoprocessamento (LAPIG – IESA / UFG), responsável pelas iniciativas de validação em campo do SIAD-AM.

Para o segundo artigo, aceito para publicação no Earth Interactions Journal, o autor, sob a orientação do Prof. Dr. Laerte Guimarães Ferreira Jr, e a colaboração do Prof. Dr. Fausto Miziara da Faculdade de Ciências Humanas e Filosofia (FCHF/UFG), selecionou o conjunto de variáveis sócio-econômicas, bem como implementou e procedeu a todas as análises estatísticas, com vistas à determinar as relações de causa e efeito entre estas variáveis e os desmatamentos observados no período de 1997 e 2005.

Para o terceiro artigo, submetido ao Remote Sensing of the Environment Journal, o autor, sob a orientação do Prof. Dr. Laerte Guimarães Ferreira Jr, e a colaboração do Dr. Alfredo Huete do *Terrestrial Biophysics and Remote Sensing Lab* (*University of Arizona*), selecionou uma área de estudo de aproximadamente 3,5 milhões de Km^2, para a qual, tendo por base um vasto conjunto de dados de desmatamentos e imagens MOD13Q1, avaliou os distúrbios resultantes sobre a paisagem, bem como a resposta dos índices de vegetação à “qualidade” (conforme métricas de paisagem) dos remanescentes de florestas.

DESCRIÇÃO DOS ESTUDOS

As respectivas revisões de literatura, descrições da área de estudo, abordagens metodológicas e conclusões estão apresentados em artigos científicos que integram esta tese. A seguir são resumidos os pontos mais importantes destes artigos.

Artigo #1: A disponibilização dos dados do *Moderate Resolution Imaging Spectroradiometer* (MODIS), especificamente o produto MOD13Q1, geograficamente referenciado, contendo índices de vegetação, bem como as respectivas informações de qualidade (i.e. metadados), além das bandas espectrais, tornaram possível o desenvolvimento do Sistema Integrado de Alerta de Desmatamentos (SIAD), utilizando como plataforma de desenvolvimento um programa computacional destinado a produção de informações geográficas, no caso o ArcGIS 9.0.

A união dos conhecimentos científicos desenvolvidos no sensoriamento remoto e na computação propiciou o desenvolvimento de novas abordagens a respeito da detecção de mudanças na cobertura florestal da Amazônia brasileira. Em fato, o processamento de imagens e/ou produtos de sensoriamento remoto em ambientes SIG é bastante favorecido com a inclusão da análise do contexto geográfico dos *pixels*. Assim, *pixels* localizados até cerca de 10 km de rodovias na floresta amazônica, e que estão mais suscetíveis a sofrerem diminuição dos seus índices de vegetação (i.e. possível ocorrência de desmatamento), uma vez que cerca de 90% dos desmatamentos e focos de calor ocorrem a esta distância de rodovias, são analisados diferentemente dos demais pixels, situados a distancias maiores da malha viária

Os resultados, após validação em campo e através de imagens de radar aerotransportadas, indicaram a viabilidade concreta de se realizar mapeamentos automáticos dos desmatamentos na floresta amazônica a partir de imagens índices de vegetação de resolução moderada. Contudo, é necessário após o processamento realizar uma inspeção visual dos polígonos de desmatamentos gerados pelo sistema, uma vez que as informações contidas nos metadados no produto MOD13Q1 podem não eliminar completamente todas as contaminações atmosféricas contidas nos *pixels*. Além disso, efeitos sazonais, regime de seca e cheia dos rios também podem levar ao mapeamento de falsos desmatamentos. Mesmo com todos esses problemas, o método desenvolvido e implementado em ambiente SIG mostrou-se bastante viável e operacional.

Artigo #2: O desmatamento mapeado a partir de imagens obtidas por sensores remotos deve ser entendido como sendo o resultado da interação homem-natureza, a qual por sua vez é ainda pouco considerada tanto nos modelos econômicos, quanto nos programas de monitoramento e combate aos desmatamentos na região Amazônica.

Em fato, a enorme dimensão geográfica desta região, a falta de controle fundiário, a baixa presença efetiva de instituições governamentais, bem como as alterações a nível regional e global de variáveis sociais e econômicas que incentivam a produção, induz ao aumento na demanda pela apropriação de terras e o conseqüente desmatamento.

Assim, análises de regressão entre as variáveis relativas à ocupação, apropriação e uso das terras e os desmatamentos, indicaram a existência de correlações significativas entre a apropriação de terras em 1995 e a ocorrência de desmatamentos no ano de 1997 e no período entre 2000 e 200, os quais são também fortemente dependentes da concentração de terras e principalmente relacionados à presença de pastagens plantadas.

Da mesma forma, as distribuições espaciais das áreas criticas dos desmatamentos (i.e. *hot spots*) são altamente correlacionadas aos *hot spots* de apropriação e concentração de terras. Por outro lado, os *hot spots* de desmatamentos são marcadas por lacunas quanto à presença das instituições responsáveis pela execução das políticas ambientais e fundiárias.

Artigo #3: O desmatamento causa consideráveis fragmentações dos habitats, alterando a diversidade e composição biológica destes e mudando processos ecológicos. Devido a todas as possíveis perturbações que os fragmentos de florestas podem sofrer, este artigo se desenvolve em torno da hipótese de que as imagens óticas de sensoriamento remoto possam registrar tais perturbações, especificamente os produtos de índices de vegetação. Assim, e tendo por base dados de desmatamentos e índices de vegetação do produto MOD13Q1 para uma área de estudo de aproximadamente 3,5 milhões de quilômetros quadrados, foram obtidas imagens do contraste sazonal, a partir de imagens MODIS relativas aos meses de maio / junho e setembro, e distúrbio da paisagem, a partir de métricas relativas a fragmentação da floresta remanescente. .

A partir das métricas da paisagem (i.e. número de fragmentos, área média dos fragmentos e tamanho das bordas), sintetizadas em uma única imagem componente principal, foi possível avaliar e quantificar os impactos dos desmatamentos à escala da paisagem. Por outro lado, e através de modelos de regressão geral e geograficamente ponderado (i.e. baseados no ajuste local das variáveis), foi possível entender como os índices de vegetação MODIS respondem à estes impactos.

Em relação aos distúrbios da paisagem, estes são particularmente evidentes nas proximidades do chamado arco do desmatamento. No que diz respeito à resposta dos índices de vegetação, considerados através dos respectivos valores de contraste sazonal, os nossos resultados sugerem que estes em fato, e principalmente o NDVI (*normalized difference vegetation index*) respondem às variações na fragmentação da paisagem, apresentando comportamento distinto entre áreas de maior e menor distúrbio.

CONCLUSÕES

Os estudos desenvolvidos no âmbito desta tese mostraram a viabilidade e a necessidade de se desenvolverem sistemas para o monitoramento da cobertura florestal, a partir da integração de imagens de sensoriamento remoto com produtos cartográficos e temáticos e dados sociais, econômicos e institucionais.

No que diz respeito aos dados de sensoriamento remoto, os resultados apresentados no apêndice 1 confirmam a possibilidade de mapearmos, de forma semi-automatizada, desmatamentos de até 50 hectares a partir de imagens índices de vegetação de resolução moderada. Neste sentido, a avaliação da qualidade atmosférica e do contexto geográfico dos pixels (ex. proximidade de estradas, etc) é imprescindível para a redução dos erros de comissão (i.e. falsas detecções) e maior precisão dos resultados.

Por outro lado, o correto entendimento do arcabouço sócio-econômico e político-institucional é uma etapa igualmente importante no processo de monitoramento e redução das tendências de desmatamentos futuros. Conforme demonstrado, os desmatamentos em áreas de florestas na Amazônia são fortemente dependentes da estrutura fundiária (i.e. apropriação e concentração de terras) e correlacionada às formas de uso (principalmente pastagens plantadas), bem como intimamente associados aos vazios institucionais que caracterizam a região. Assim, e conforme os dados apresentados no apêndice 2 desta tese, os índices de desmatamentos na Amazônia, atualmente em torno de 17.800 km2 anuais, só começarão a ser reduzidos mediante uma melhor presença e atuação do Estado, com vistas à efetiva governança da região, e uma estrutura fundiária que garanta a presença dos pequenos ocupantes de terras, principais vitimas da violência e das migrações em busca de novas fronteiras.

Por fim, e conforme demonstrado no apêndice 3, um sistema de monitoramento para a Amazônia deve considerar tanto o mapeamento dos desmatamentos, quanto a qualidade e viabilidade ecológica dos remanescentes de florestas. Em fato, e conforme observado, florestas remanescentes altamente fragmentadas são “descapitalizadas”, tanto no seu sentido ecológico, quanto econômico, o que resulta em um comprometimento da floresta bastante superior aos desmatamentos mapeados através de dados de sensoriamento remoto.

APÊNDICE 1

A Geographical Oriented Deforestation Mapping System for the Brazilian Amazon Region.

Artigo submetido ao Remote Sensing of Environment Journal

An operational deforestation mapping system using MODIS data and

spatial context analysis*

Nilson Clementino Ferreira [a]
Laerte Guimarães Ferreira [a]
Alfredo Ramon Huete [b]
Manuel Eduardo Ferreira [a]

[a] Federal University of Goias - UFG
Social and Environmental Studies Institute - IESA
Campus Samambaia - Cx. Postal 131 CEP: 74001-970 Goiania, GO, Brazil
E-mails: ncferreira@uol.com.br, laerte@iesa.ufg.br, manuel@iesa.ufg.br

[b] Department of Soil, Water, and Environmental Science
University of Arizona, Tucson, AZ 85721, USA
E-mail: ahuete@ag.arizona.edu

Abstract

The Brazilian Amazon has the world's highest absolute rate of forest loss, currently averaging nearly two million hectares per year. In this study, we present a near real-time automated deforestation mapping system for the Brazilian Amazon based on the analysis of spatial context information and MODIS Vegetation Index products and implemented on an ArcGIS 9.0 platform. This system, already validated and operational, was developed as part of the "Integrated Warning Deforestation System for the Amazon" (SIAD), an initiative of the Brazilian government within the scope of the Amazon Protection System (SIPAM), which also comprises a 1) spatial information module, aimed at the assessment of the causes and impacts of the deforested areas; 2) a prediction module, indicative of deforestation trends, and 3) a data and information gateway based on map server technology.

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Keywords: Deforestation; Vegetation index; Geographic context

1. Introduction

Deforestation in the Amazon Forest, the largest remaining tropical forest ecosystem on Earth, began in the second half of the 20th century in response to the substantial increase in immigration driven by the construction of large road networks and governmental colonization projects. In the early 1970´s, logging activities grew in importance with the expansion of intensive agricultural and cattle ranching favored by economic incentives and greater access to markets (Laurance et al., 2001). Although these incentives have been either reduced or redirected toward social and environmental issues, rapid rates of deforestation continue today. In fact, the Brazilian Amazon has the world's highest absolute rate of forest loss, currently averaging nearly two million hectares per year (INPE, 2000).

These rapid changes in land cover and land use conversions in Amazon ecosystems have major impacts on global carbon and water cycles, energy balance, and influences global climate regulation (Potter et al., 2001).

As a result, deforestation activity has been closely monitored since 1978 with the aid of remote sensing technology, mostly based on Landsat MSS, TM and ETM+ imagery. One major initiative is a project known as PRODES[1], directed by the Brazilian Institute for Space Research (INPE), which has been, mapping forest clear cuts on a yearly basis since 1989 (Shimabukuro, Y. E., 2000). In 2003, PRODES geographical data on Brazilian Amazon deforestation in forested areas (i.e. without considering the savanna

[1] - Deforestation mapping program

vegetation) were made available through the internet[2].

In spite of the many positive results accomplished with efforts like PRODES, there are several intrinsic and extrinsic drawbacks in the remote sensing data which limit the effectiveness of deforestation monitoring of the Amazon. The low spatial resolution of the NOAA-AVHRR data and the large errors inherent in the normalized difference vegetation index (NDVI) time series data sets (poor sensor calibration, poor pixel location, insufficient cloud screening, and variable acquisition geometry) seriously impede to their utilization for Amazon studies (Goward et al., 1991; Moody and Strahler, 1994). Landsat TM and ETM+ imagery, on the other hand, offer much better quality data sets, but at infrequent intervals to capture the dynamics of the fast changing Amazon region. The acquisition and processing cost of 227 Landsat scenes in the Amazon region that has persistent cloud in the rainy season and smoke contamination during the dry seasons, limit the utility of Landsat based deforestation monitoring.

This gap in timely data availability has been dramatically reduced by the MODIS sensor, onboard both the Terra and Aqua satellites launched in December 1999 and May 2002, respectively (Justice et al., 1998). This MODIS sensor was designed to provide information on the dynamics of the Earth's biosphere with a global coverage every two days and spatial resolutions varying from 250m to 1000m. MODIS has 36 spectral bands, including seven that are spectrally similar to the ETM+ bands.

An important characteristic of the MODIS data is its "ready-to-use"

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[2] - http://www.obt.inpe.br/prodes/

format; i.e., the data is atmospherically corrected, cloud screened, and geocoded, and is made available at no cost in the form of different standard data products, including the “MOD13” vegetation indices (VI).

In order to circumvent many of the shortcomings in current deforestation assessments, in this paper we present the framework and initial results of a near real time automated deforestation mapping system for the Brazilian Amazon Forest, implemented on a GIS platform (ArcGIS 9.0) and based on the comparative analysis of MODIS 250m VI (MOD13Q1) images and spatial context information. This system was developed within the scope of the federal government’s Amazon Protection System (SIPAM) and is part of a larger initiative, the Integrated Warning Deforestation System for the Amazon, known as SIAD. SIAD includes the following components: 1) a spatial information module based on the analysis of social, economical, environmental and institutional data for assessing the origin and impacts of deforested areas; 2) a prediction module indicative of deforestation trends, and 3) a data and information gateway based on map server technology.

2. The MOD13 Products

The MOD13 VI products are designed to provide consistent spatial-temporal measures of photosynthetically active vegetation, and comprise two VIs: the NDVI, produced to extend the AVHRR-NDVI time series, and the enhanced vegetation index (EVI), a new index designed to be resistant to residual atmospheric noise and canopy background effects (Huete et al., 1994; Liu and Huete, 1995). As demonstrated in different studies (e.g. Huete et al., 1997), the NDVI is highly correlated to the fraction of absorbed photosynthetically active radiation, while the EVI shows canopy structural variations and is particularly optimized to function in dense vegetation regions (Didan, 2004; Huete et al., 2002).

The MODIS VI products are available in a variety of spatial and temporal resolutions (table 1). With the exception of the climate modeling grid (CMG, 0.05^{o}), MOD13C1 and MOD13C2, products, the MOD13 datasets are delivered as tiles of approximately 1200 x 1200km, in the sinusoidal cartographical projection.

Table 1. Characteristics of the MOD13 products.

Product	Temporal Resolution	Spatial Resolution	File Size	Science Data Sets / Bands
MOD13Q1	16 days	250 meters	508 mb/tile	11 SDS
MOD13A1	16 days	500 meters	128 mb/tile	11 SDS
MOD13A2	16 days	1000 meters	32 mb/tile	11 SDS
MOD13A3	30 days	1000 meters	32 mb/tile	11 SDS
MOD13C1	16 days	0.05^{o}	544 mb/global	12 SDS
MOD13C2	30 days	0.05^{o}	544 mb/global	12 SDS

The algorithm behind the MODIS VI´s operates on a pixel basis, taking into account multiple observations within a 16 days period. Due to the orbital overlapping and multiple observations in a single day, up to 64 observations can be obtained for each pixel. However, after the cloud contaminated and large view zenith angle observations are eliminated, only about 5 to 10 observations are considered useful for the process of compositing, in which the best pixel is selected (i.e. closest possible to nadir viewing and with the least degree of aerosol and cloud contamination) (van Leeuwen et al., 1999). The VI products are accompanied with Science Data Sets (SDS) of ancillary information, including solar zenith angle, sensor view angle, and quality assurance (QA) metadata layers that describe on a per pixel basis, the quality of the reflectance input data and computed VI output data (table 2).

Table 2. Science data sets (SDS) provided by the MOD13Q1 (250m), MOD13A1 (500m), MOD13A2 (1000m), and MOD13A3 (1000m) products.

	SDS	Units	Data (bit)	Fill Value	Valid Range	Scale Factor
Vegetation Indices Images	NDVI	NDVI	16-bit *integer*	-3000	-12000	10000
	EVI	EVI	16-bit *integer*	-3000	-12000	10000
Reflectance Images	Red	reflectance	16-bit *integer*	-1000	0-10000	10000
	Infrared (NIR)	reflectance	16-bit *integer*	-1000	0-10000	10000
	Blue	reflectance	16-bit *integer*	-1000	0-10000	10000
	Infrared (SWIR)	reflectance	16-bit *integer*	-1000	0-10000	10000
Metadata	NDVI *Quality (QA)*	*bit field*	16-bit *unsigned integer*	65535	0-65534	none
	EVI *Quality (QA)*	*bit field*	16-bit *unsigned integer*	65535	0-65534	none
	View Zenith Angle	Degree	16-bit *integer*	-10000	-18000	100
	Solar Zenith Angle	Degree	16-bit *integer*	-10000	-18000	100
	Azimuth	Degree	16-bit *integer*	-4000	-7200	10

3. The Amazon Region: Social-economical and Environmental Settings

The Amazon forest, located in the northern region of Brazil, between 5º north and 14º south latitude and 44º and 74º west longitude, has a territorial extension of about 4,040,000 km^2 and encompasses nine States (Maranhão, Pará, Tocantins, Amapá, Amazonas, Acre, Roraima, Rondônia and Mato

Grosso) and 473 municipalities, which, according to the 2000 census data, have a population of approximately 15.600.000 people, mostly concentrated in the urban areas (about 67%).

The natural land cover of Amazon landscapes is classified into three main vegetation physiognomies, determined primarily by their proximity to the rivers,

- *mata de igapó*: submersed forest, permanently flooded;
- *mata de várzea*: a mixture of vegetation species, temporarily flooded;
- *mata de terra firme*: dense and humid forest formations encountered in most upland parts of the Amazon region.

Some of the largest rivers in the world traverse and drain the Amazon rainforests, including the Solimões, Negro, Amazonas, Tapajós, Tocantins, Madeira, Purus, Juruá, which, along with their thousands of tributaries, make the Amazon basin one the most irrigated regions on Earth (Latrubesse et al., 2005). These rivers not only maintain and support the Amazon forests, but are a source of fresh water to the local population and serve as important regional transportation network.

The population living in the Amazon region is mostly concentrated within the southern and eastern fringes of the forest, where intensive agriculture, cattle ranching and logging dominate economic activity (figure 1). There also exists significant population concentrations along the major rivers of central Amazonia, however, seasonal flooding render these areas less susceptible to deforestation. As a result, the economy of these regions has been traditionally focused on industrial activities (e.g. Manaus).

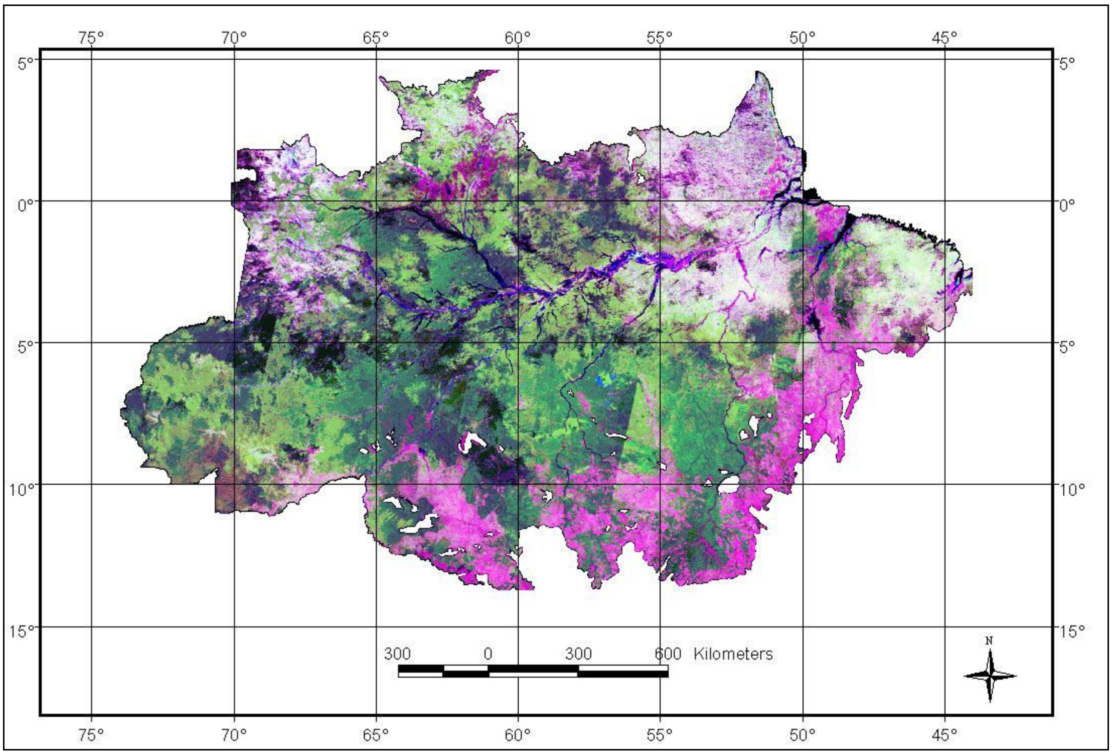

Figure 1. August 2004 MODIS color composite (*NIR, MIR* and *Red* reflectance bands from MOD13Q1), in which it is possible to see forest converted areas along the southern and eastern edges of the forest (in red / magenta shades).

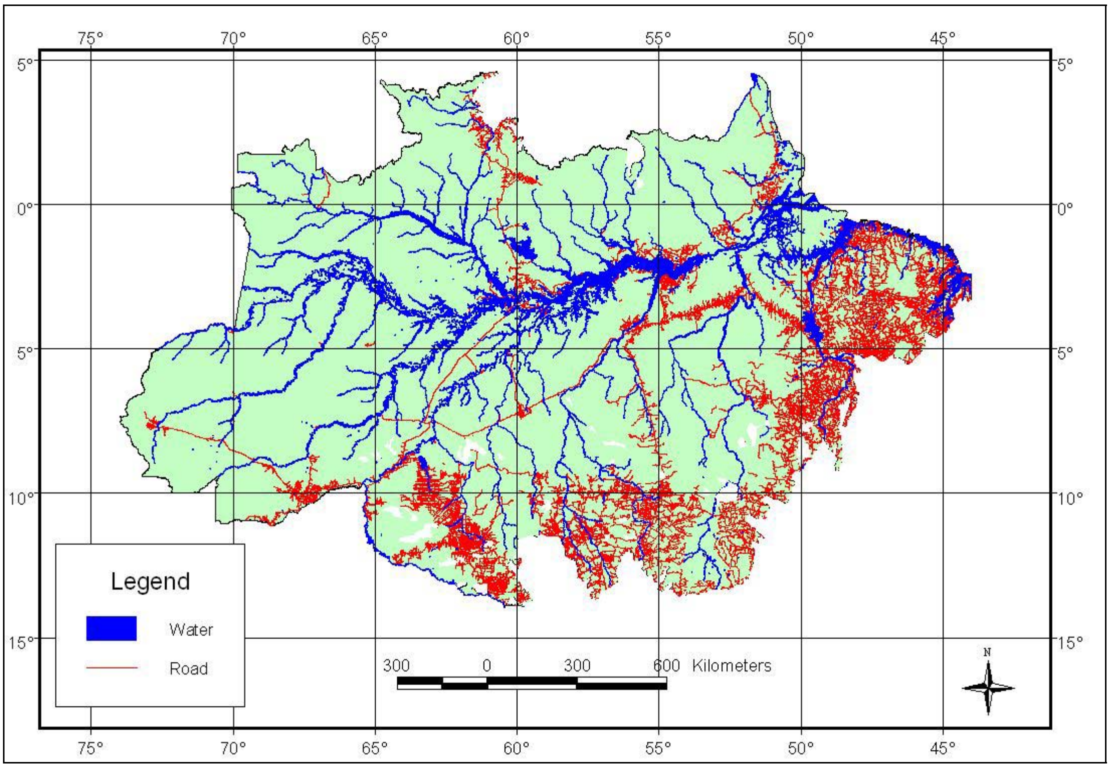

Figure 2. Major road (red) and drainage (blue) network in the Amazon forest.

As shown in figure 2, the road network across the Amazon basin is mostly located in the southern and eastern regions and is strongly correlated with the PRODES deforestation maps from 1989 through 2003 (figure 3) as well as deforestation as seen in figure 1.

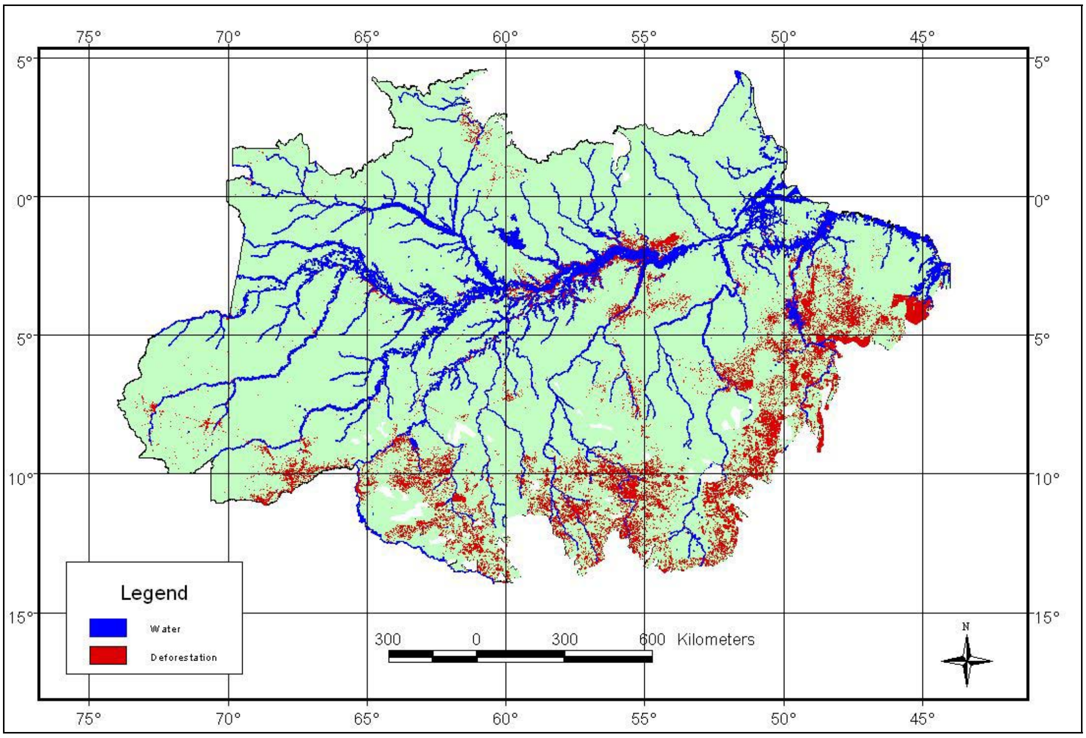

Figure 3. Forest clearcuting for the 1989 – 2003 period. Source: PRODES - INPE.

Hotspots of potential burning occurrences, which are closely associated with forest clearcutting, and agriculture and pasture management practices (Nepstad et al., 1999), also show a similar pattern, i.e. they also tend to concentrate close to roads (Fig. 4).

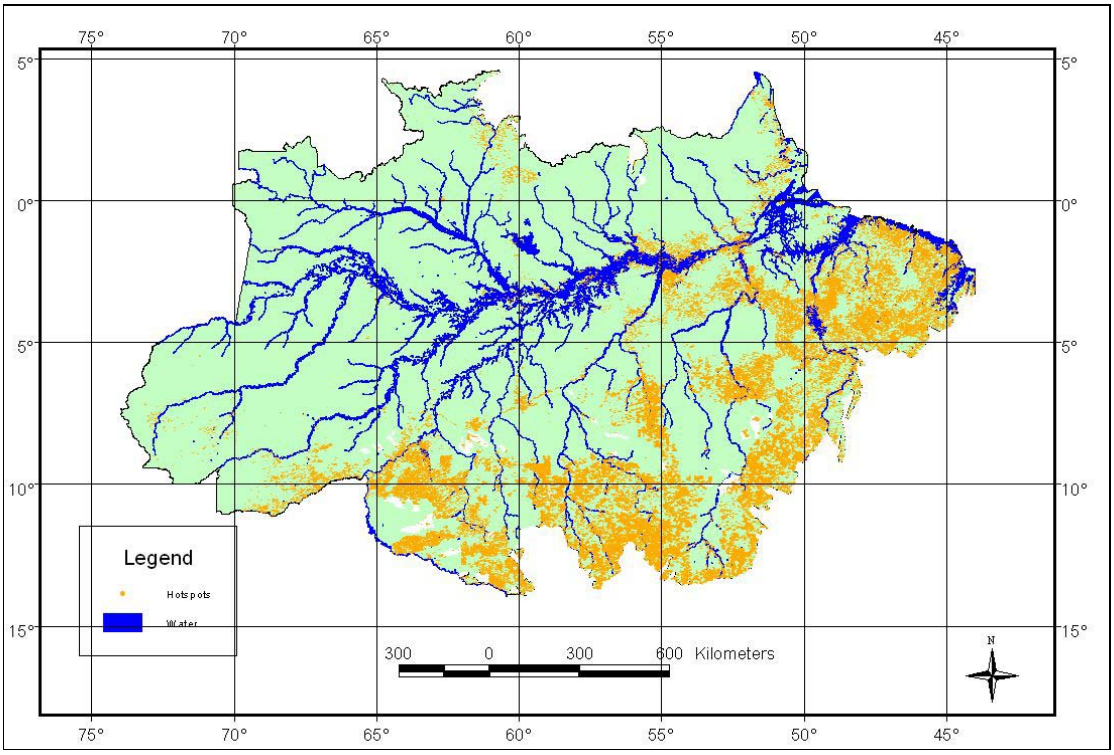

Figure 4. Hotspot occurrences in the Amazon forest for the year 2004.

Source: CPTEC / INPE.

4. An Automated Deforestation Mapping System Based on Geographical Information

Conceptual Framework

A major difficulty in automated processing of orbital images involves the occurrence of ambiguities, which may result in either omission or commission (i.e. false detections) errors in the detection of deforestation events. In this regard, our automated deforestation mapping application is based on the comparative analysis of MODIS VI images, such that both intrinsic changes in the VI values, related to modifications in the vegetative cover, as well as variations in the VI values caused by atmospheric noise (i.e. aerosols, cloud, and shadows) are considered. Furthermore, any significant change in the VI value is spatially checked in order to prevent "false" detections in areas previously deforested.

Our approach based on geographic context, also considers the relative proximity of pixels to the road network. This is accomplished with an ArcGIS 9.0 geographical information system platform that facilitates the analysis of relationships between the road network, deforestation, and burning. A preliminary assessment based on a distance map indicates that about 90% of all the forest conversion between 1989 and 2003 and hotspot detections in 2004 are located within a 10km distance from any existing road (figures 5 and 6).

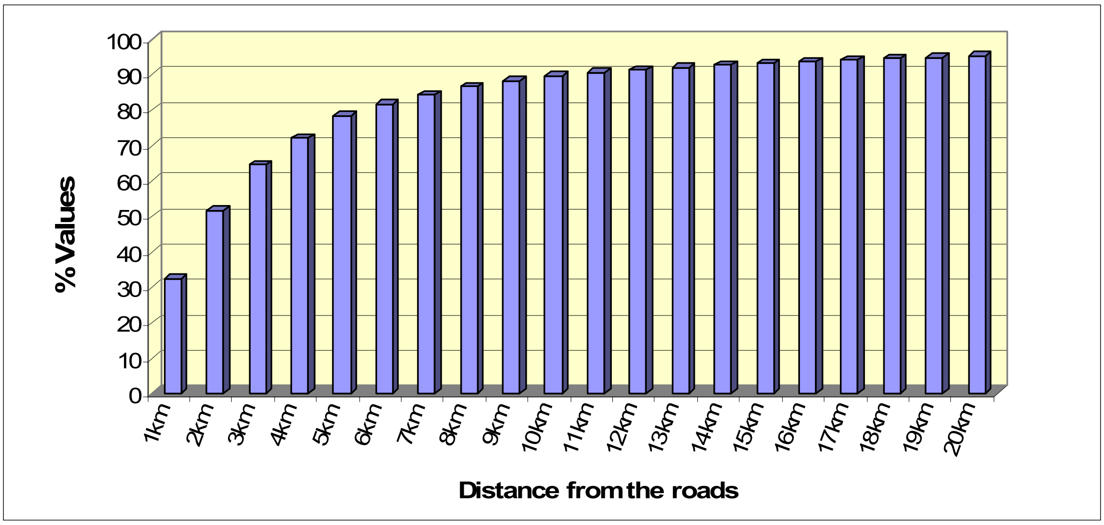

Figure 5. Percent deforestation from 1989 to 2003 in relation to distance to the road network.

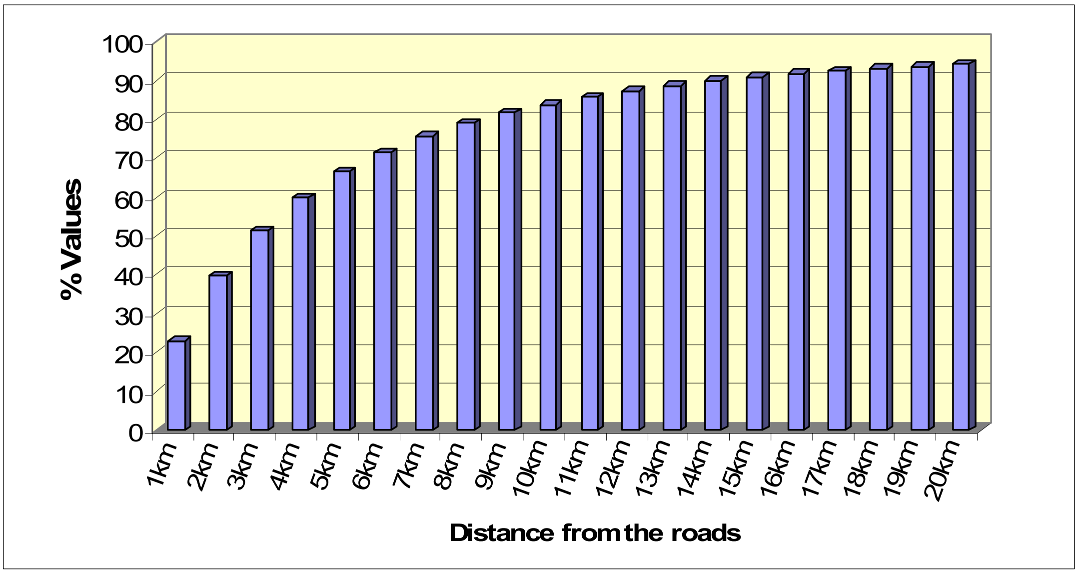

Figure 6. Hotspot occurrences in 2004 in relation to distance to the road network.

Whereas most deforestation assessments are conducted annually or are restricted to certain locations, in this study we developed an automated deforestation mapping system that provides more rapid estimates, at any given time period, over the entire Amazon basin.

Widespread cloudy conditions in the Amazon region impose severe constraints on forest monitoring based on optical remote sensing such as MODIS data (Asner, 2001). The analysis of monthly 1 km VI (MOD13A2) metadata from August 2002 through August 2004 suggests that residual cloud and shadow cover are approximately 60% from November through March (Ferreira et al, 2005). On the other hand, excessive precipitation amounts (2250 to 2750mm a year) also form natural barriers to large scale deforestation, dependent on heavy machinery and burnings. Thus, cloud cover and forest burning activities in the Amazon show an inverse behavior, as depicted in figure 7.

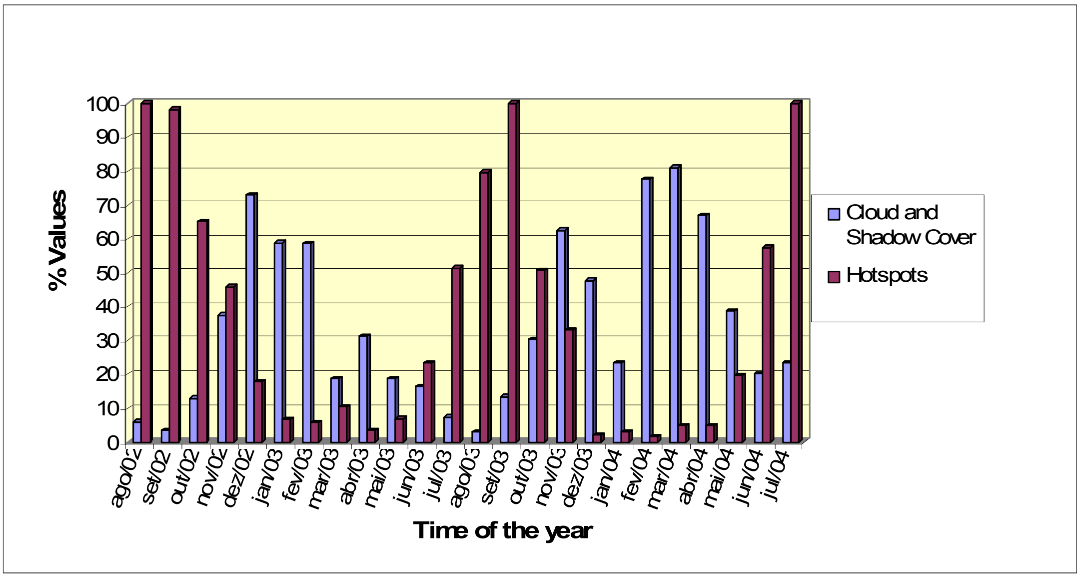

Figure 7. Seasonal patterns of hotspot occurrences and cloud / shadow cover, from MOD13A2 metadata, over the Amazon for the years of 2003 and 2004.

4.1 Specifications and Algorithm

The rationale behind the automated mapping approach is shown in figure 8. First it is necessary to select and acquire, via ftppull, the 250m VI (MOD13Q1) products. For the complete deforestation mapping of the Amazon forest, 11 tiles are used for each date (i.e. T1 – “old” - and T2 – “new”) (figure 9). The second step involves the definition of basic parameters by the user, such as the location of the MODIS image files (T1 and T2 data sets), the path of the temporary folders, etc.

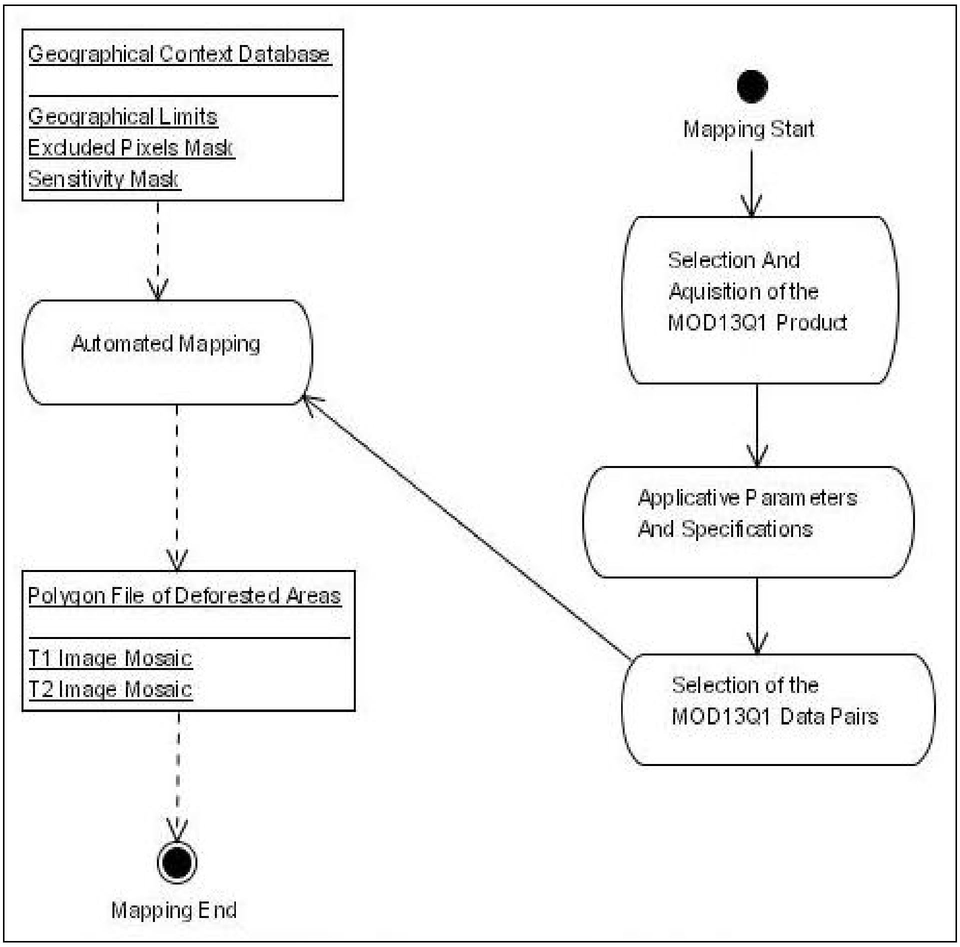

Figure 8. Flow diagram depicting the main steps in the automated deforestation mapping.

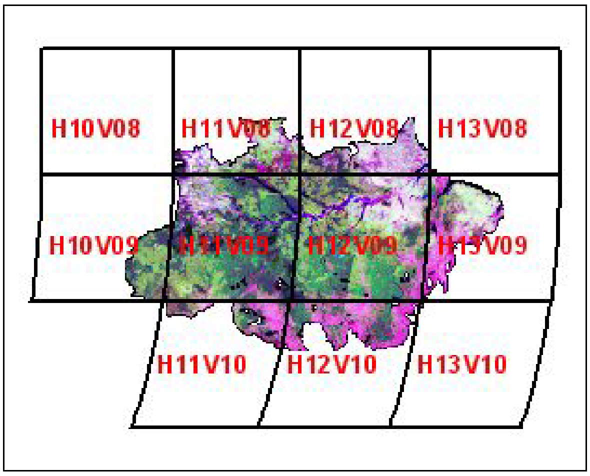

Figure 9. MOD13Q1 tiles used for deforestation mapping of the entire Amazon forest.

After all the necessary parameters have been defined, the user selects the pairs of MOD13Q1 tiles that will be analyzed. In this analysis that will be performed automatically, ancillary geographical information stored in image format at 250m spatial resolution, is also considered along with the MODIS VI images. This includes: a) the Amazon forest boundary limits, b) a mask of areas already converted as well as water bodies, and c) a “change sensitivity” mask, which applies a 10% change threshold to all pixels situated within a 10km buffer around any road and a more conservative 40% threshold to all the other pixels located at distances greater than 10 km from a road (figure 10).

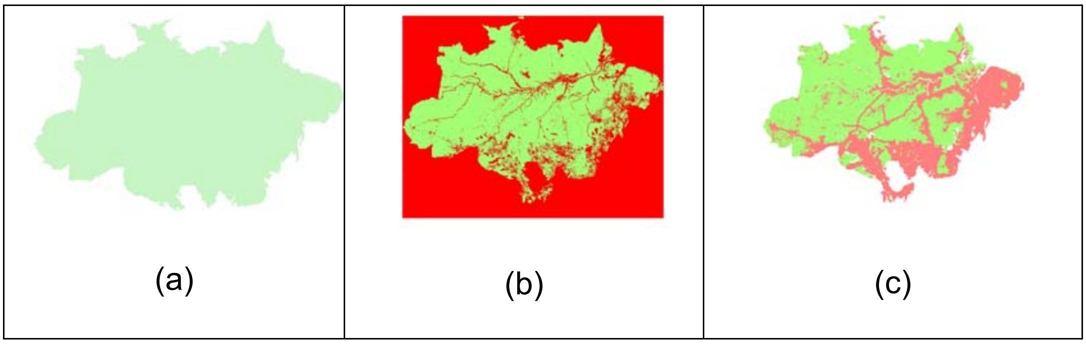

Figure 10. Geographical context maps. (a) Amazon forest geographical limits; (b) Map of the areas considered in the deforestation mapping, in which the green indicate the areas that will be analyzed, while the areas in red correspond to water bodies or areas already converted; (c) Change threshold map, in which the areas in red correspond to high change sensitivity (i.e. 10% change threshold) and the areas in green are of low sensitivity (i.e. 40% change threshold).

All the processing is conducted according to the flow chart shown in figure 11. At first, all the respective T1 and T2 data sets (i.e. VI´s, QA layers, and the Red, NIR, and MIR reflectance images) are mosaicked and converted from the sinusoidal projection to the geographical coordinate system, as well as from the HDF[3] data structure to the GeoTiff format.

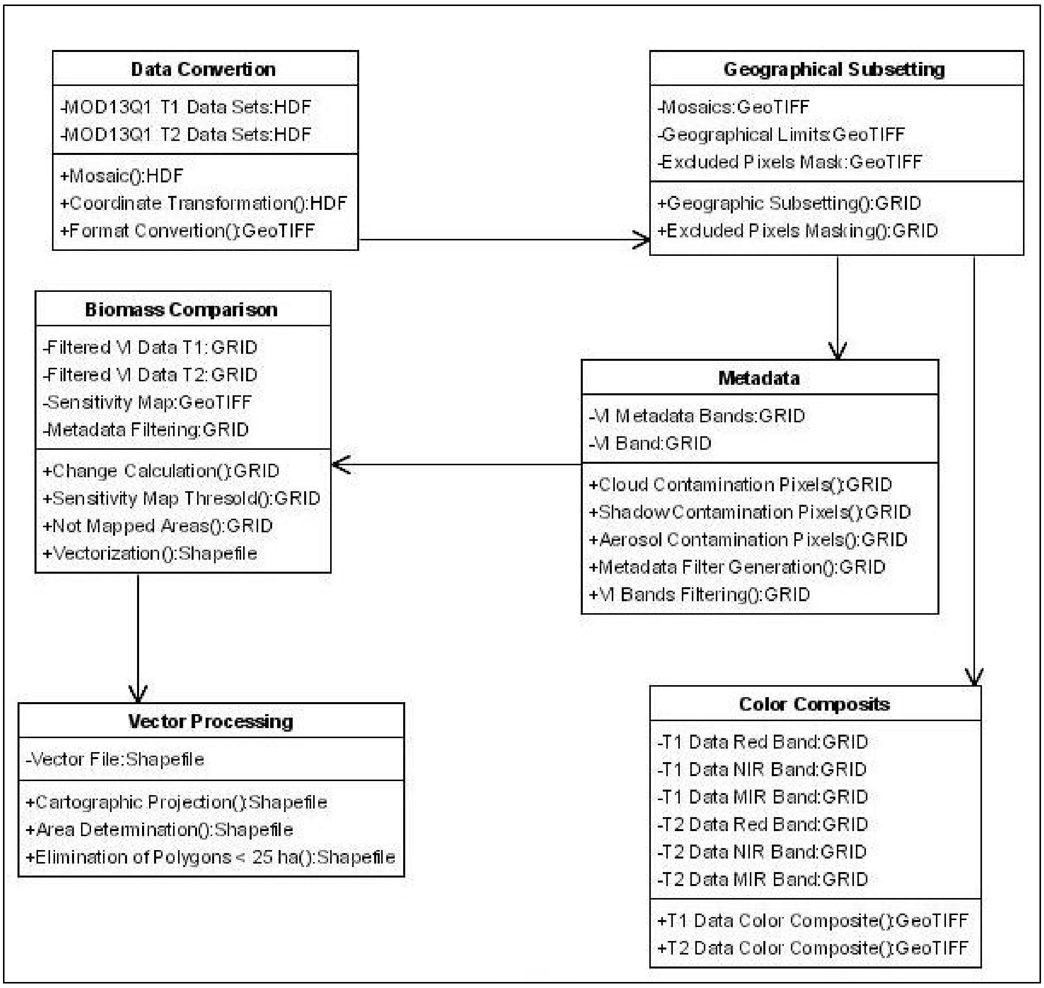

Figure 11. Flow chart diagram depicting the main processing phases for the automated deforestation mapping.

The T1 and T2 mosaics are then adjusted to the geographical limits of the Amazon forest and all the pixels coincident with water bodies or areas previously converted, according to the respective masks, are eliminated.

[3] - Hierarchical Data Format

Following this step, the metadata images, for both the T1 and T2 dates, are converted to binary values so that the quality information can be decoded and properly used. In particular, we consider the bit-fields 4, 6, and 7 to identify the pixels contaminated with aerosols and the bit-fields 10 and 14 to determine which pixels have either cloud or shadows, respectively. Based on all the pixels contaminated with aerosol, cloud, or shadow, from either the T1 or T2 data sets, an image-mask is created and applied to the T1 and T2 VI images in order to eliminate the low quality pixels (i.e. the respective VI value becomes null).

After this extensive filtering of the data, the T1 and T2 VI images are compared for determining if there was, from T1 to T2 a relative change in the vegetative cover:

$$Dif\,(\%) = \frac{VI_{T1} - VI_{T2}}{VI_{T1}} \times 100 \qquad (1)$$

where Dif (%) is VI difference, between T1 and T2, in percentage values; VI_{T1} is the VI value for the time T1; and VI_{T2} is the VI value for the time T2.

From equation 1, three situations are possible: 1) VI_{T1} and VI_{T2} are very close to each other and the Dif (%) is near zero; i.e. there was no significant change in vegetation; 2) VI_{T1} is larger than VI_{T2}, indicating a possible deforestation, and 3) VI_{T1} is smaller than VI_{T2}, indicating a possible gain in biomass eventually related to secondary growth.

This preliminary vegetation difference map is then compared with the sensitivity change image (i.e. change threshold image). If the difference in VI value is greater or equal to 10% and falls on an area of high change sensitivity (i.e. within a 10 km buffer around any road), the pixel is associated with deforestation. On the other hand, for those areas of low change sensitivity (i.e. situated more than 10 km away from any road), the pixel is considered to be deforested only if the respective reduction in VI value is greater than 40%. The pixels that were discarded from this analysis due to contamination by cloud, shadow or aerosol, receive a classification value distinct from the deforested pixels so that they can also be included in the resultant binary image (table 3).

Table 3. Pixel categories after the analysis for determining potential changes in the vegetation cover.

Pixel Category	Description
0	No deforestation detected
1	Possible deforestation in area of high change sensitivity
2	Possible deforestation in area of low change sensitivity
1000	Non-processed pixel due to residual cloud contamination, etc

After all pixels have been classified, the raster structure data is automatically converted to a vector layer and the pixels from a same category replaced by polygons, whose attribute values are equivalent to the respective category. Once the polygon map is completed, it is temporally projected, in a dynamic manner, to the Albers conical equivalent projection, so that the area of each polygon can be precisely calculated. Based on this information, all the polygons smaller than 25ha are eliminated.

Finally, the application generates two Red, NIR, and MIR color composite mosaics (for the T1 and T2 dates), which are useful for the visual inspection of the deforestation map and enables eventual errors to be manually eliminated or edited.

5. Validation Results

The deforestation mapping system described in the previous session has been validated through two complementary approaches: a comparative analysis with airborne SAR data and a fieldwork campaign in the State of Rondônia. The SAR data was acquired by the L-band SAR of the SIPAM instrument, at VV polarization mode and 6m spatial resolution, over Lábrea (State of Amazonas) and Porto Velho (State of Rondônia) in July, 2004 (figure 12), and compared to the MOD13Q1 h11v09 tile (June-July 2004 compositing period). As shown in figure 13a and b, the clear cut areas are well depicted by both the MODIS and SAR – SIPAM imagery, in spite of the resolution differences between these two systems. The high spatial accuracy and information content of the MOD13Q1 product is illustrated in figure 13c, which depicts part of the h11v09 MODIS color composite overlaid by the SAR-SIPAM imagery. In particular, the deforestation polygon automatically mapped by our system (i.e. SIAD) accurately matches the forest conversion patch observed in the SAR images (figure 13d).

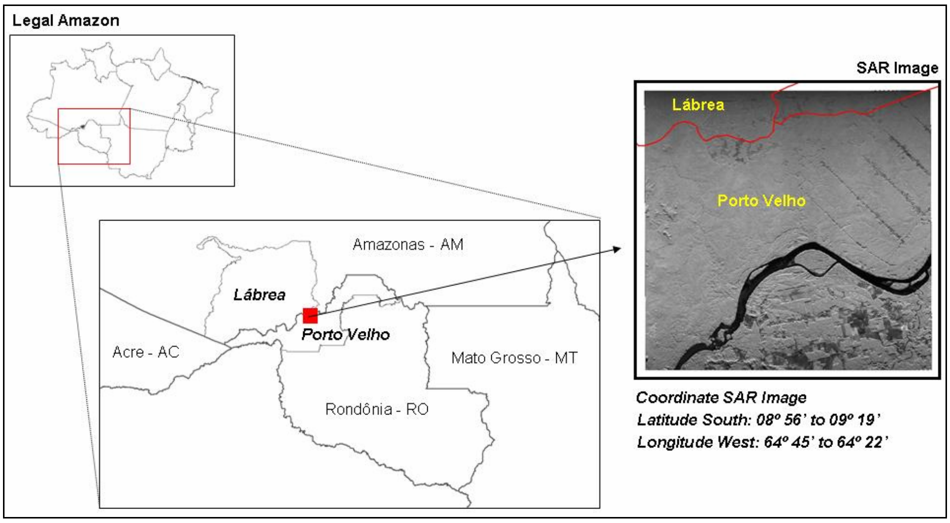

Figure 12. SAR data acquired over Lábrea (State of Amazonas) and Porto Velho (State of Rondônia) in July, 2004.

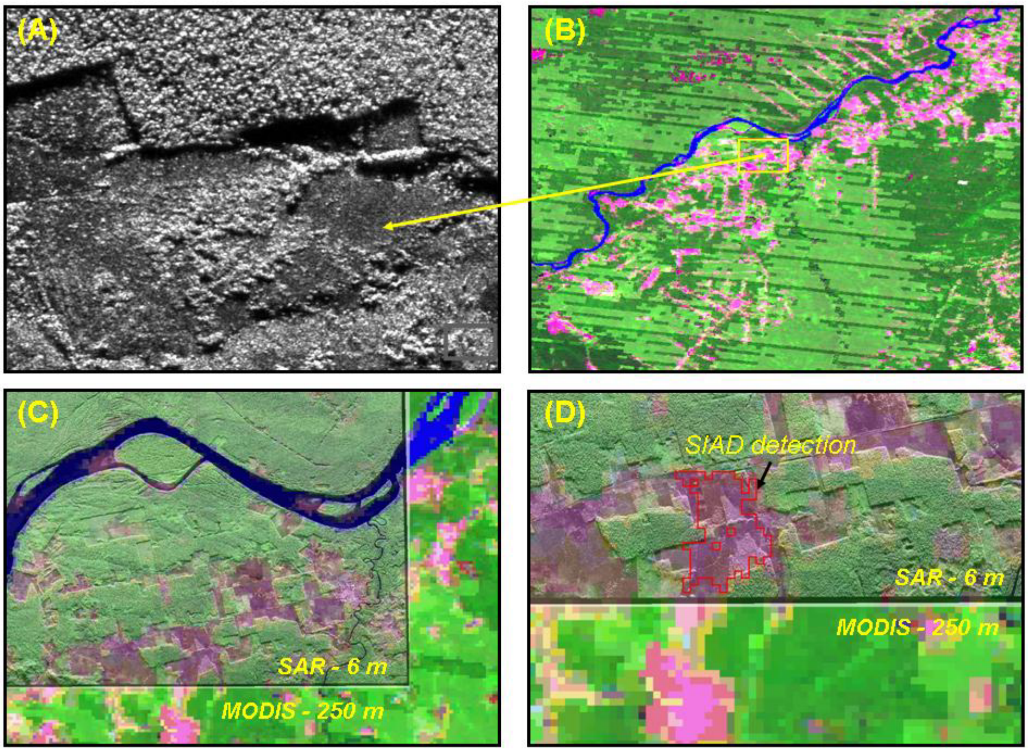

Figure 13. Clear cut area depicted by the SAR – SIPAM (A) and the MODIS (RGB/MIR,NIR,Red) (B) imagery; MODIS color composite (RGB/MIR,NIR,Red) overlaid by the SAR-SIPAM imagery (C), and a

deforestation polygon automatically mapped by SIAD matching the forest conversion patch observed in the SAR – MOD13Q1 integrated image (D).

The Rondônia fieldwork took place from May 23 to June 03, 2005 and used to evaluate the MOD13Q1 NDVI detections for the August - September 2004 period (figure 14). Overall, 282 "SIAD" detections were visually inspected for the region around Porto Velho, corresponding to approximately 14,664 ha of presumed deforestation, while 77 polygons related to both small settlement areas, as well as large cattle ranching activities (equivalent to about 4,489 ha) were ground-truthed during the first and second weeks of field work, respectively.

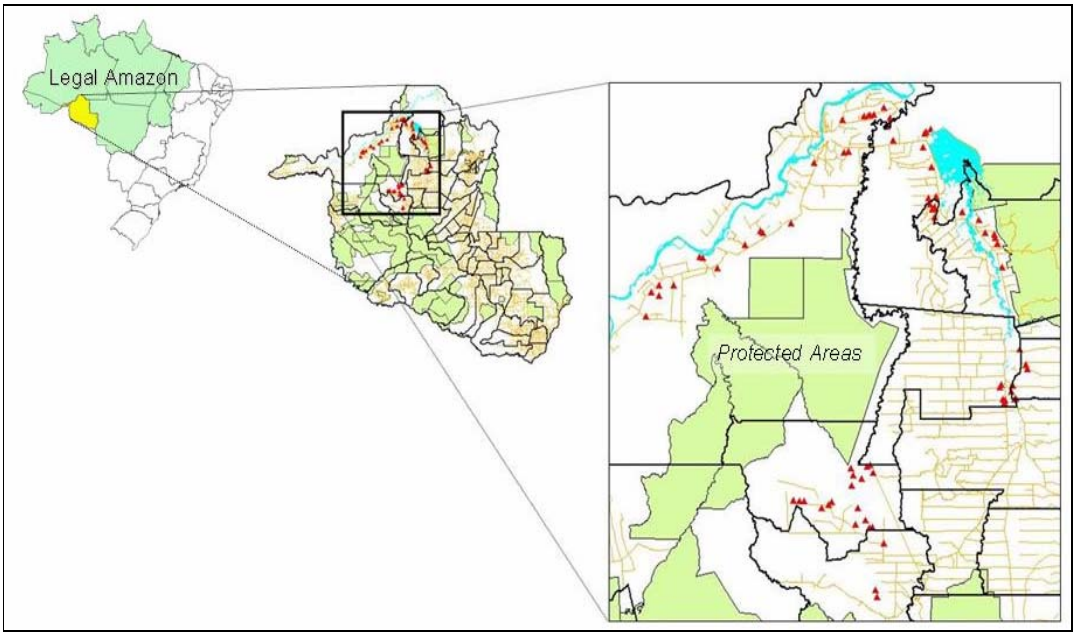

Figure 14. Location of the fieldwork in Rondônia, from May 23 to June 03, 2005, based on the MOD13Q1 NDVI detections for the August - September 2004 period.

For the rural settlement areas, the average size clearings ranged from about 25 to 50 ha, and were mainly associated with pasture maintenance and family agricultural practices. As seen in figure 15, of the 27 SIAD polygons investigated within this size category, 30% were true forest conversion, 26% were associated with pasture clearings, 37% were related to seasonal vegetation changes, and 7% were assumed to be “true” classification errors, due to both sensor and SIAD noises. Over the large pasture sites (i.e. second week of campaign), from the 41 polygons inspected, 33% were true forest conversion, 48% were associated with pasture clearings, and 19% were related to normal seasonal changes (figure 16).

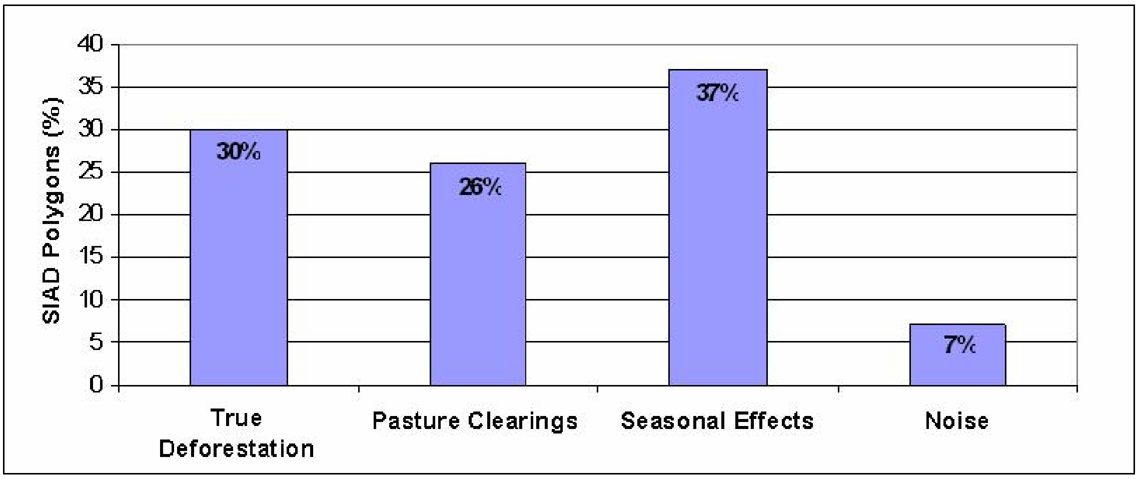

Figure 15. % of the SIAD (presumed) deforestation polygons (total of 27 polygons located in small settlement and family agricultural areas) falling into one of the following ground-truth evaluation classes: true deforestation, pasture clearings, seasonal effects, and noise

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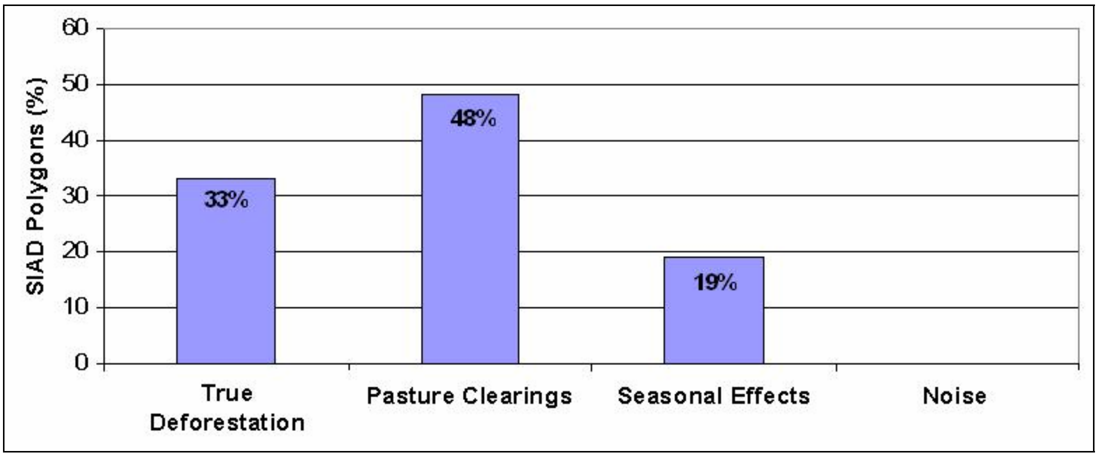

Figure 16. % of the SIAD (presumed) deforestation polygons (total of 41 polygons located in large pasture areas) falling into one of the following ground-truth evaluation classes: true deforestation, pasture clearings, seasonal effects, and noise.

On the other hand, a more careful interpretation of the data shown in figures 15 and 16, suggests that the overall accuracy of SIAD is above 70 % on average, as both the misclassifications due to seasonality and pasture clearings can be significantly reduced according to the change threshold, the land cover mask, and the time period (i.e. T1 and T2) being compared. The 10% change threshold used in this validation run, made the system very sensitive to any subtle variation in the vegetative cover, such as those caused by seasonality, which is particularly significant in the area of study, even for the one month time lag between T1 and T2. The land cover mask used to prevent detections over previously deforested areas, contributed about 37% of the false detections (i.e. the % of detections related to pasture clearings) and is in need of further improvement.

Finally, our attempt to identify change polygons as small as 25 ha, which corresponds to 5.6 MOD13Q1 pixels, is certainly beyond the mapping capability of the MODIS sensor. Thus, change polygons between 25 and 100 ha should only be taken as potential deforestation and be used as a guide for further analysis at higher spatial resolutions.

6. Concluding Remarks

It is estimated that biomass burning in the states of Legal Amazonia can result in nearly 1 Pg of carbon (Pg = 10^{15} grams) released into the atmosphere each year (Hao and Lui, 1994; Potter et al., 2001). Likewise, perturbations (such as fertilization) that accompany conversions of forests to agricultural land use may reduce soil CH_4 and CO sinks (Bender and Conrad 1994), and elevate NO emissions, which play a major role in tropospheric dynamics and regional atmospheric chemistry. Therefore, a major global environmental requirement is the systematic and effective monitoring of the Amazon forest in order to prevent or at least reduce the dramatic rate of forest loss, of approximately two million hectares per year.

Within this scope, this paper describes a newly developed application for the systematic monitoring of forest areas in the Amazon region, involving a unique approach that considers both satellite imagery as well as a wide variety of ancillary geographic information and their spatial context. As clearly demonstrated in this paper, deforestation follows very predictable spatial and temporal patterns (e.g. along roads, etc.), which can be easily accommodated into a geographical information system.

This application, already in use by the Amazon Protection System, is part of a larger initiative, the Integrated Warning Deforestation System for the Amazon (SIAD), which also comprises a 1) spatial information module, aimed at the assessment of the causes and impacts of the deforested areas; 2) a prediction module, indicative of deforestation trends, and 3) a data and information gateway.

Our on going validation exercises, based on high spatial resolution airborne SAR data, ETM+ imagery, and field work confirm the high precision and accuracy of our mapping approach, which certainly offers promising opportunities to the effective monitoring and preservation of the Amazon forest.

Acknowledgements

This work was developed as part of a larger initiative of the Brazilian Government, through the Amazon Protection System, aimed at the monitoring and prevention of deforestation in the Amazon. During the course of this research, the second author received a fellowship of the Brazilian Research Council (CNPq).

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APÊNDICE 2

Deforestation hotspots in the Brazilian Amazon: Evidences and causes as assessed from remote sensing and census data.

Deforestation hotspots in the Brazilian Amazon: Evidences and causes as assessed from remote sensing and census data [*]

Nilson Clementino Ferreira
Laerte Guimarães Ferreira
Fausto Miziara

Federal University of Goiás (UFG)
Social and Environmental Studies Institute (IESA)
Image Processing and GIS Lab (LAPIG)
Campus II, Cx. Postal 131, Goiania, Goiás, CEP 74001-970, Brazil
ncferreira@uol.com.br – http://www.ufg.br/lapig

Abstract

The main goal of this study, conducted in an area comprising 221 municipalities, in which 90% of the deforestation in the legal Amazon takes place, was to understand the role of the agrarian structure in the conversion of forest into pasture and agriculture fields. Linear regression results indicate that 54% to 62% of the variation in deforestation occurred between 1997 and 2004, respectively, are explained as a function of changes in the amount of appropriated land in 1995. Likewise, up to 80% of the deforestation can be well explained by the variation in land concentration. In fact, strong spatial correlations were found between deforestation hotspots and land appropriation and land concentration. On the other hand, these critical areas have insufficient governance, particularly at the federal level. As our results clearly demonstrate, strong governance and institutional integration, with emphasis on the territorial ordainment, are mandatory in order to reduce the rapid pace of deforestation in the Brazilian Amazon.

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1. Introduction

The Amazon region, due to its territorial dimensions, large fluvial system, and an extensive forest cover, has a major influence on global carbon exchange, energy balance, and climate regulation (Potter et al., 2001; Costa & Foley, 2000; Houghton et al., 2000; Williams, 1997). On the other hand, rapid changes in land cover, driven by governmental projects aimed to foster land occupation and economic activities, have been taking place over the Amazon ecosystems since the early 1970's (Skole et al., 1994). Interestingly, even after the boom of such initiatives and the adoption of environmental policies concerning the conservation of the natural resources in the 1990's, the pace of forest conversion didn't decrease. In fact, clearcutting rates are continuously increasing, currently approaching nearly two million hectares per year (INPE, 2000).

Although these deforestations have been closely monitored since 1978 with the help of remote sensing technology (e.g. Skole and Tucker, 1993), and significant attempts have been made in order to understand their causes and possible trends (e.g. Pfaff, 1999; Alves et al., 2003), the relationship between deforestation and land tenure remains largely unexplained.

Within this context, and assuming that land appropriation is a major driving force behind deforestation, a major goal of this study was to understand, on a large scale basis and through the integrated analysis of social and economical variables and deforestation data obtained via remote sensing imagery, the role of the land ownership structure on the Amazon deforestation. In particular, the deforestation distribution patterns along the years, and their spatial dependence on land appropriation, land concentration, and land use were investigated. Likewise, the current institutional context (i.e. governance) of the Amazon region and its geographical relation to potential deforestation hotspots was also evaluated.

2. Study Area

The area of study, encompassing 221 municipalities located in the forested portions of the Brazilian Amazon, corresponds to approximately 3.25 millions of km^2 (i.e. 81% of the Legal Amazon region), and is responsible for about 92% of all the deforestations occurred so far. Particularly important in choosing this area was also the availability of a complete time series of census data, from 1970 to 1995, as well as deforestation data, since 1997(Figure 1).

The selected area, entirely located inside Brazil, is limited by six South American countries: Bolivia, Peru, Colombia, Venezuela, Guiana e Suriname. The total population is around 9,378,787 people, from which, about 73% are found in urban areas, while the 27% remaining live in rural areas.

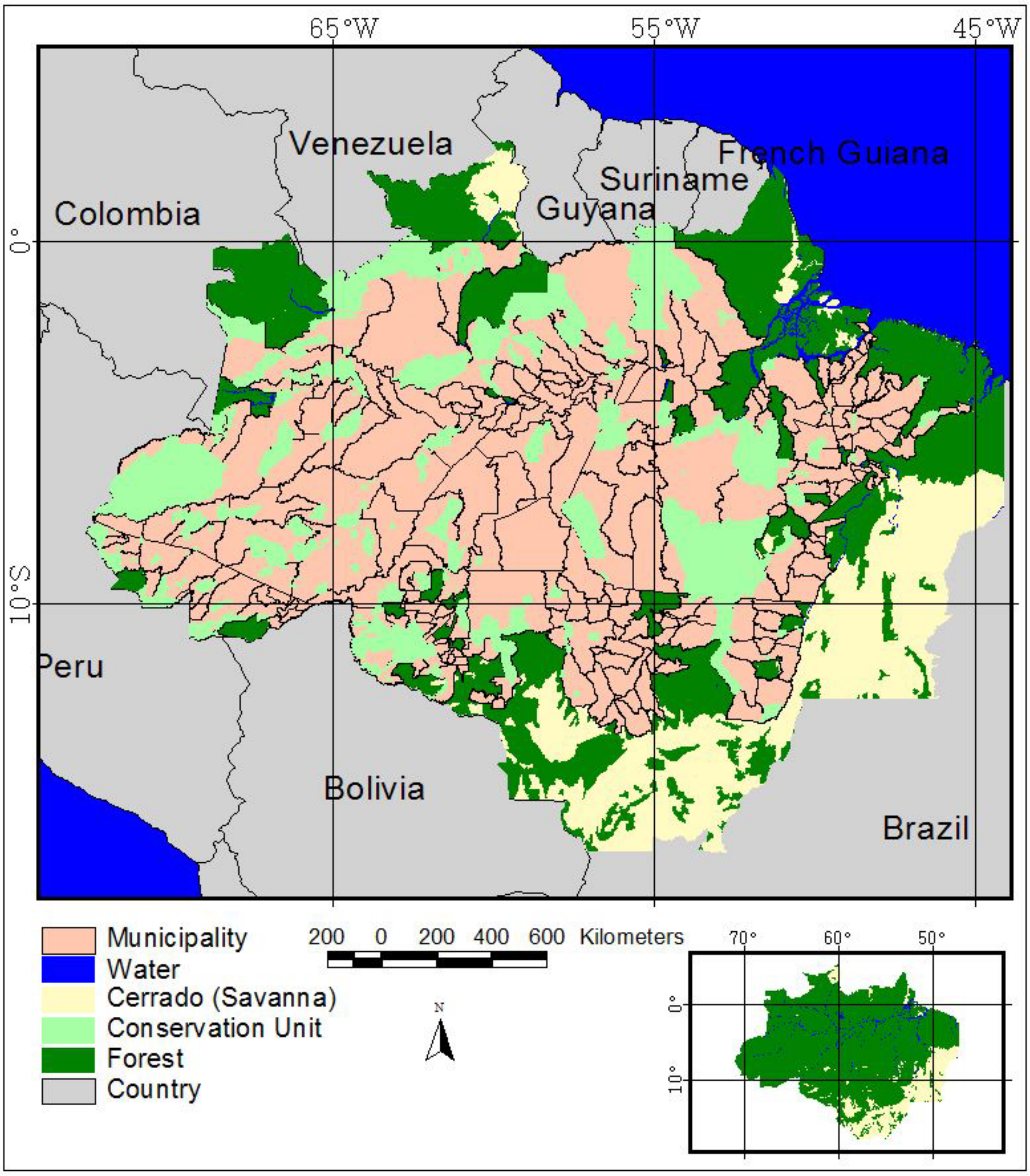

Figure 1 – Study area and highlight of the 221 municipalities it comprises (shown in pink)

Another important characteristic of the study area is the 879,023.22 km^2 of sustainable use and integral protection conservation units and indigenous land, which correspond to about 27% of the area under analysis and 63% of all the protected areas in the Legal Amazon.

Regarding land conversion, in 1997 it corresponded to 6.7% of the study area, while in 2004 it reached 10.31%. On average, the annual deforestation rate is about 17,800 km^2 (Figure 2).

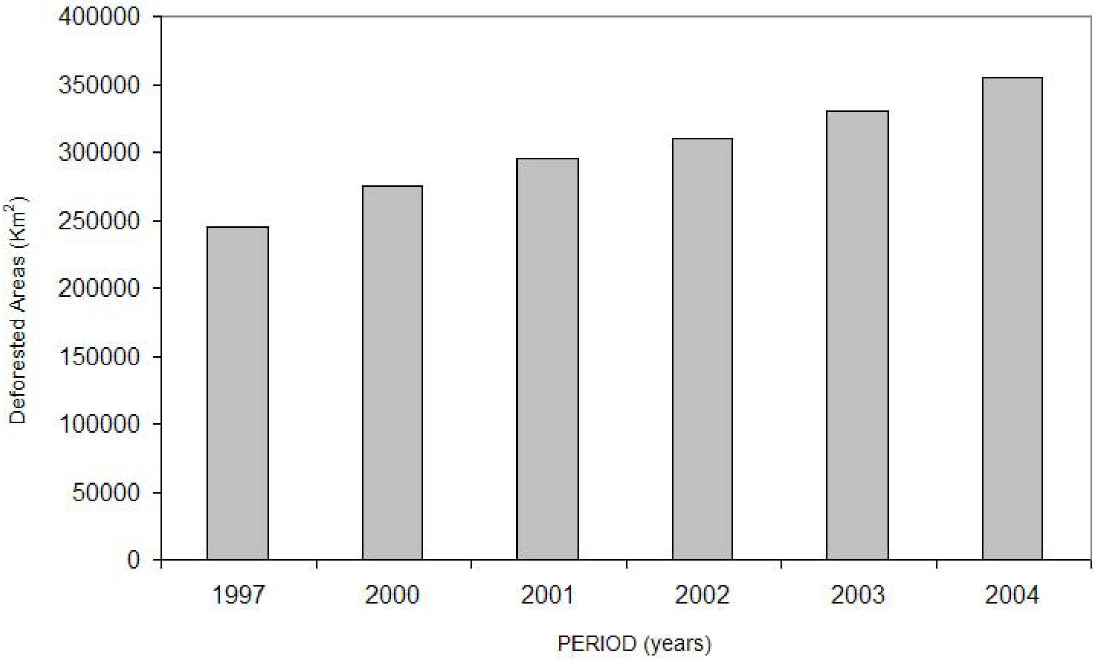

Figure 2 – Deforestation in the study area between 1997 and 2004 (source: INPE / PRODES data)

3. Data Description

3.1 Deforestation Data

The deforestation data utilized in this study were those obtained from the Brazilian Space Research Institute (INPE) PRODES (Deforestation Monitoring Program) and DETER (Detection in Real Time), and the Amazon Protection System (SIPAM) SIAD (Integrated Warning Deforestation System) initiatives. The PRODES data, available in vector format for the year of 1997 and from 2000 through 2004, is based on Landsat imagery (Shimabukuro et al., 2000), while the DETER (Anderson et al., 2005) and the SIAD data (Ferreira et al., 2006), available since 2004, are based on MODIS 250m reflectance based-endmembers and vegetation index images, respectively.

3.2 Census Data

Information on land ownership (i.e. land owner or land occupant), agricultural revenue and land use (cultivated and natural pastures, and temporary and permanent crops), were obtained from the agricultural and cattle-raising census data, made available by the Brazilian Institute of Geography and Statistics (IBGE)[4], at the municipality level, for the period between 1970 and 1995.

Additional cartographical data, such as municipal limits, road network, map of conservation units and location of public institutions (e.g. IBAMA – the Brazilian Institute of the Environment and Renewable Natural Resources, etc) were obtained from the digital compilations prepared by the IBGE for the SIPAM.

4. Data Analysis

The comprehensive thematic, cartographic, and census datasets were organized into a geographical information system (GIS) and integrated with the municipal layer in order to establish a common basis between deforestation, conservation units, institutions and road maps with the spatialized social-economical variables (Figure 3).

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[4] www.ibge.gov.br

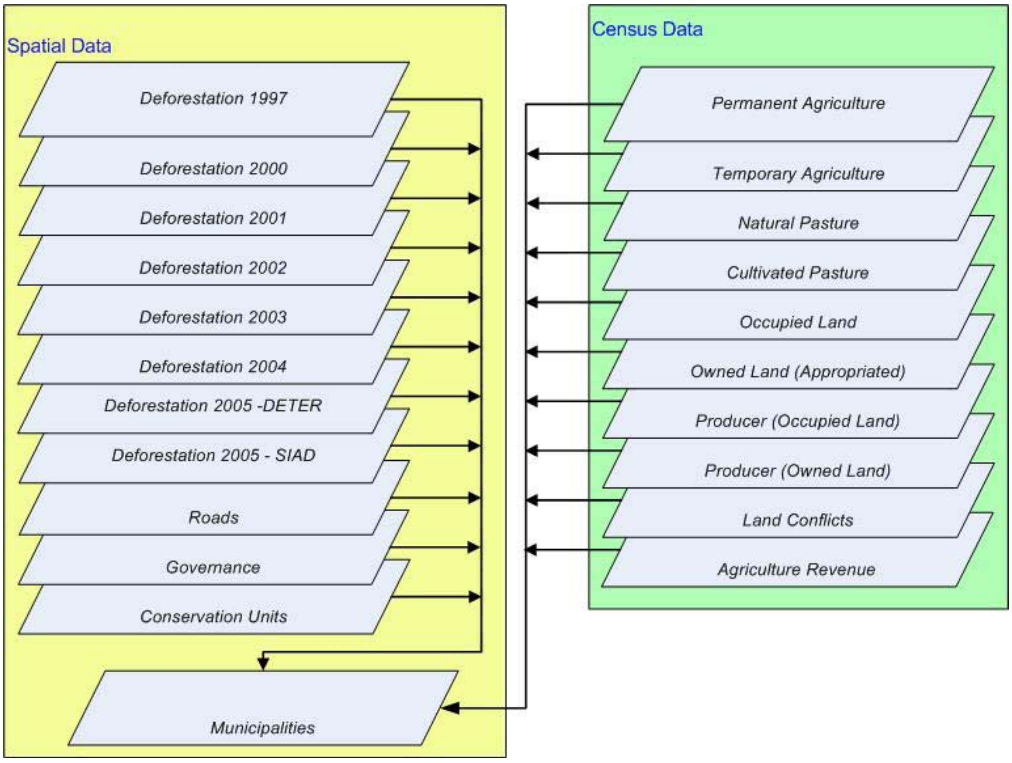

Figure 3 – Integration data model regarding the cartographic, thematic, and census datasets

The main approaches and steps followed in this study are depicted in Figure 4.

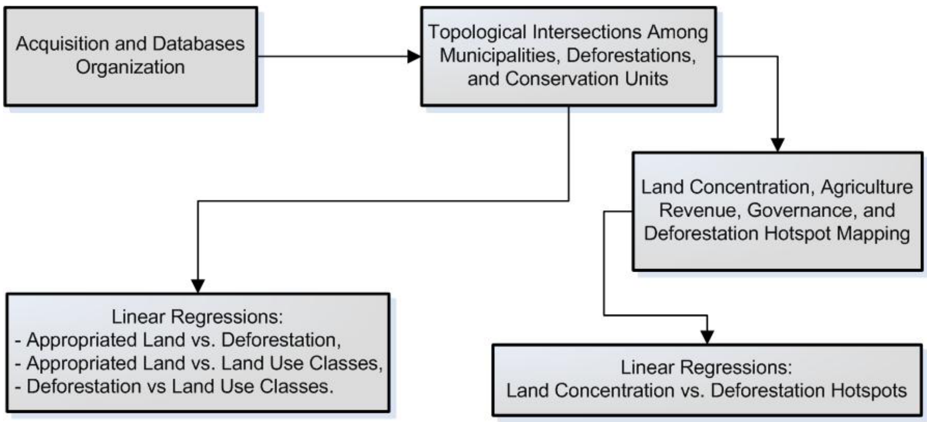

Figure 4 – Flow chart diagram depicting the main approaches and steps in the present study

The relationship between land appropriation and deforestation was assessed through linear regressions, taking into account only the percentage of appropriated land for each municipality not coincident with conservation units or Indian reserves. The deforestation and land appropriation amounts were also evaluated regarding the land use classes (e.g. natural and cultivated pastures, etc).

The identification of critical areas (*hotspots)* concerning land concentration[5] and deforestation, as well as the analysis of the respective spatial correlations, were based on the use of the Getis-Ord measure, which identifies clusters of low and high values regarding local spatial associations (Getis and Ord, 1992). The Getis-Ord approach can be described as a ratio between the summation of neighboring values in a certain area and the summation of all values in the sample, as shown in equation 1:

$$Gi = \frac{\sum_j w_{ij}(d)x_j}{\sum_j x_j} \qquad (1)$$

where $w_{ij}(d)$ are the elements in the contiguity matrix for a distance d

Hotspots maps were produced for land concentration and agricultural revenue, according to the 1995 agricultural census, governance, and the deforestation detected between 1997 – 2000, 2000 – 2001, 2001 - 2002, 2002 - 2003, and 2003 - 2004, based on Landsat imagery (i.e. PRODES initiative), and between 2004 – 2005 using the MODIS products (i.e. DETER and SIAD initiatives).

[5] The average land concentration for each municipality was obtained through the ratio between the appropriated area and the number of land owners.

The correlation between deforestation and land concentration was estimated based on linear regressions of the respective Gi cluster values associated to each municipality.

The degree of governance in the study area was assessed through the IBAMA and INCRA (Brazilian Institute of Colonization and Agrarian Reform) offices, in charge of conducting and enforcing the federal government environmental and agrarian reform policies, respectively, and the SIPAM communication network, located in a variety of governmental institutions and distributed all over the Legal Brazilian Amazon.

Specifically, the geographical area of influence of each institution branch / terminal, regardless of their jurisdictions, was mapped through a set of Thiessen polygons (Thiessen and Alter, 1911; Gold, 1991). The respective governance hotspots were determined based on the inverse of the area of these polygons.

5. Results and Discussion

5.1 Land Appropriation

In the study area, appropriated land (i.e. owned) predominates over occupied areas. As seen in Figure 5, this difference continuously increased since 1970 . Interestingly, while the land appropriation showed a systematic and strong increment, the occupied areas varied much less and at a slower pace, suggesting that land appropriation, besides the replacement of small land occupants, occurs mainly on public pristine lands.

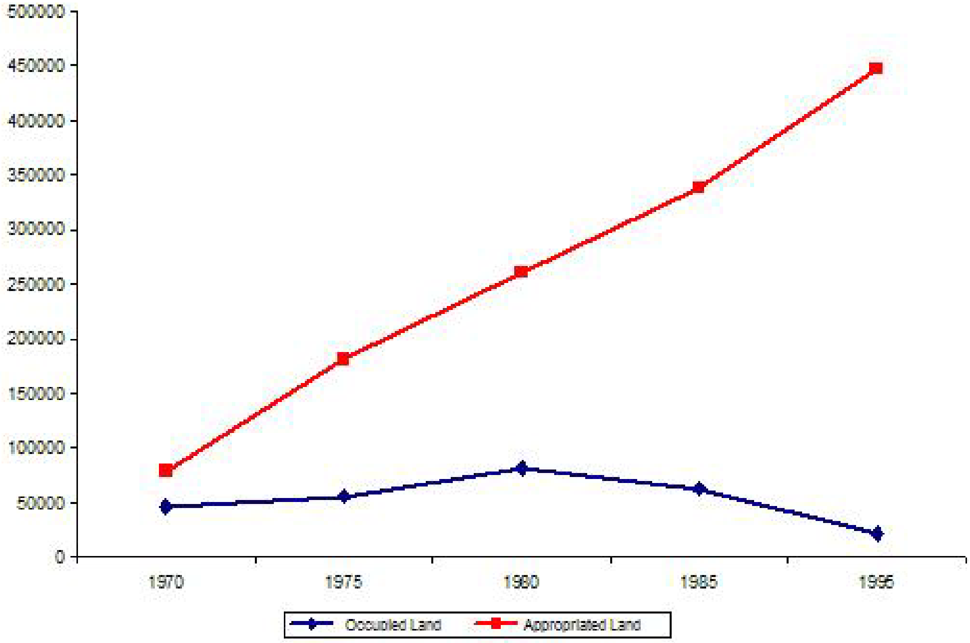

Figure 5 – Evolution of appropriated and occupied land in the study area, for the period between 1970 and 1995 (source: IBGE)

5.2 Land Appropriation and Deforestation

The relationship between land appropriation in 1995 and the accumulated deforestation in 1997, 2000, 2001, 2002, 2003, and 2004 are presented in Table 1. It is worthwhile to notice that the deforestation dependence on the appropriated land increases slightly from 1997 to 2004, as indicated by the r^2 values and the respective angular coefficients of the regression lines, indicating a certain time lag between variations in the agrarian structure and deforestation.

Table 1 – Relationship between land appropriation (x) and accumulated

deforestation (y)

Year	Model (y = ax + b)	r^2
1997	y = 0.5278x + 0.0027	0.5410
2000	y = 0.6094x + 0.0016	0.5888
2001	y = 0.6237x + 0.0071	0.5986
2002	y = 0.6411x + 0.0096	0.6067
2003	y = 0.6564x + 0.0141	0.6162
2004	y = 0.6769x + 0.0203	0.6255

The spatialized regression residuals for the deforestations occurred until 1997 are shown in Figure 6. As seen in this Figure, deforestation behaves as predicted in 54% of the municipalities, i.e. according to the variations in the land appropriation values, while only 2% of the samples behave as outliers in relation to the proposed model.

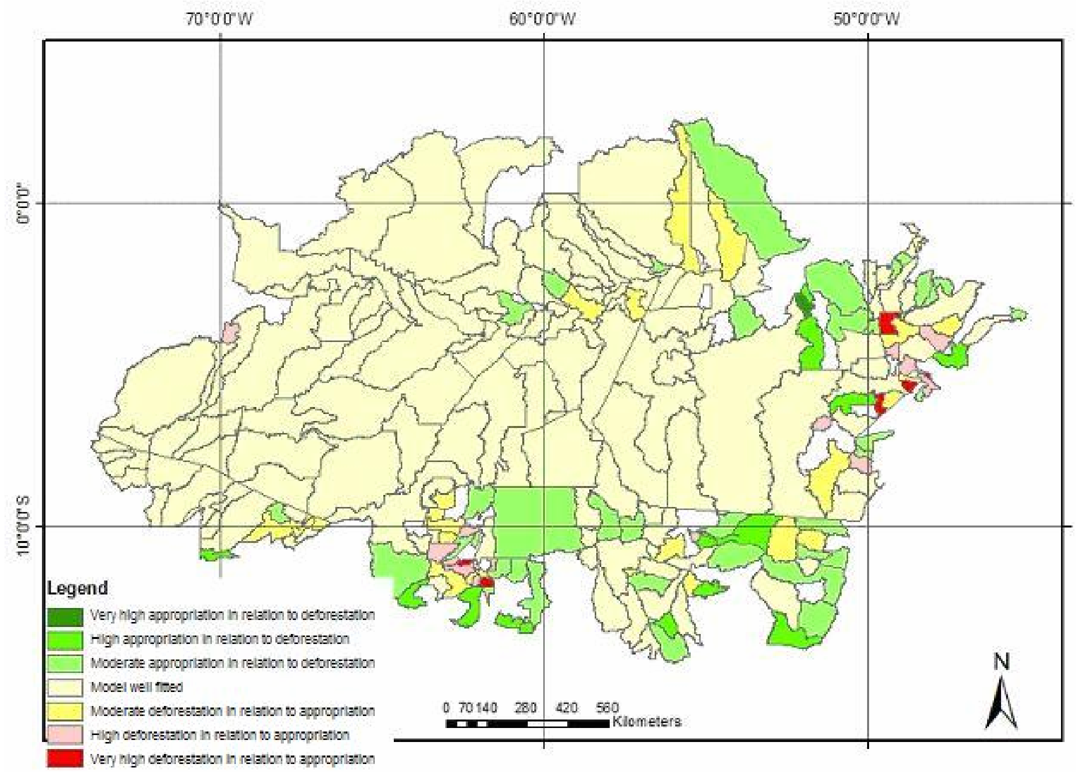

Figure 6 – Residual map yielded by the regression model between land appropriation (1995) and the deforestation detected until 1997

5.3 Land Use, Land Appropriation, and Deforestation

As observed in Table 2, deforestation and land appropriation are most strongly correlated to cultivated pastures. In fact, in relation to other land cover types, such as permanent crops, cultivated pastures demand fewer resources and infra-structure and are more easily consolidated.

Table 2 – Linear regression results regarding the correlations among land use, land appropriation, and deforestation

Land Use (y) e Land Appropriation (x)		
Land Use	Regression Model y = ax + b	R^2
Permanent Crops	y = 0.0201x + 0.0011	0.1079
Temporary Crops	y = 0.0316x + 0.0015	0.0952
Native Pastures	y = 0.0427x + 0.0038	0.1122
Cultivated Pastures	y = 0.3998x – 0.0288	0.7757

Year	Deforestation (y) and Temp. Crops (x)		Deforestation (y) and Cultivated Pastures (x)	
1997	y = 1.1529x + 0.1623	R^2 = 0.033	Y = 1.0973x + 0.0475	R^2 = 0.605
2000	y = 1.3734x + 0.1923	R^2 = 0.036	Y = 1.2888x + 0.0589	R^2 = 0.628
2001	y = 1.4115x + 0.2038	R^2 = 0.036	Y = 1.3254x + 0.0654	R^2 = 0.630
2002	y = 1.4426x + 0.2129	R^2 = 0.036	Y = 1.3686x + 0.0698	R^2 = 0.631
2003	y = 1.4824x + 0.223	R^2 = 0.036	Y = 1.3996x + 0.0767	R^2 = 0.630
2004	y = 1.5417x + 0.2363	R^2 = 0.036	Y = 1.4376x + 0.0863	R^2 = 0.623

5.4 Land Concentration and Deforestation

A significant characteristic of the agrarian structure of the Brazilian Amazon is the size of the rural properties. In some areas, a small number of farmers owns significant extensions of land. According to the 1995 IBGE agricultural census, the average land concentration in the nine Amazonian States is about 255% larger than in the other 18 states in Brazil.

The close dependence between land concentration and deforestation is confirmed by the hotspots analysis. In the map shown in Figure 7, it is possible to observe that the land concentration hotspot (areas in red) comprises 42 municipalities located in the State of Mato Grosso and in the Southern region of the Pará State.

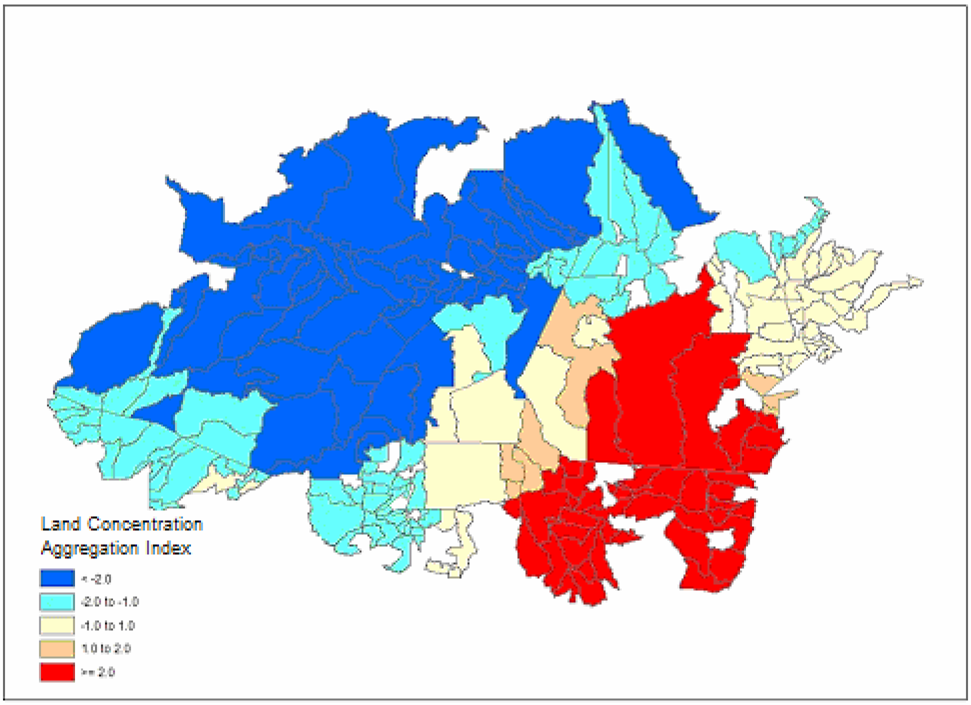

Figure 7 – Hotspot map of land concentration, where municipalities with values equal or greater than 2 (in red) are classified as hotspots, while municipalities with values equal or smaller than -2 (in blue) are classified as coldspots

The hotspot maps regarding the deforestations occurred between 1997-2000, 2000-2001, 2001-2002, 2002-2003, 2003-2004 (PRODES data), and 2004- 2005 (DETER and SIAD data) are shown in Figure 8, while the correlation between deforestation and land concentration, according to the regression of the respective hotspot G_i values, is shown in Table 3.

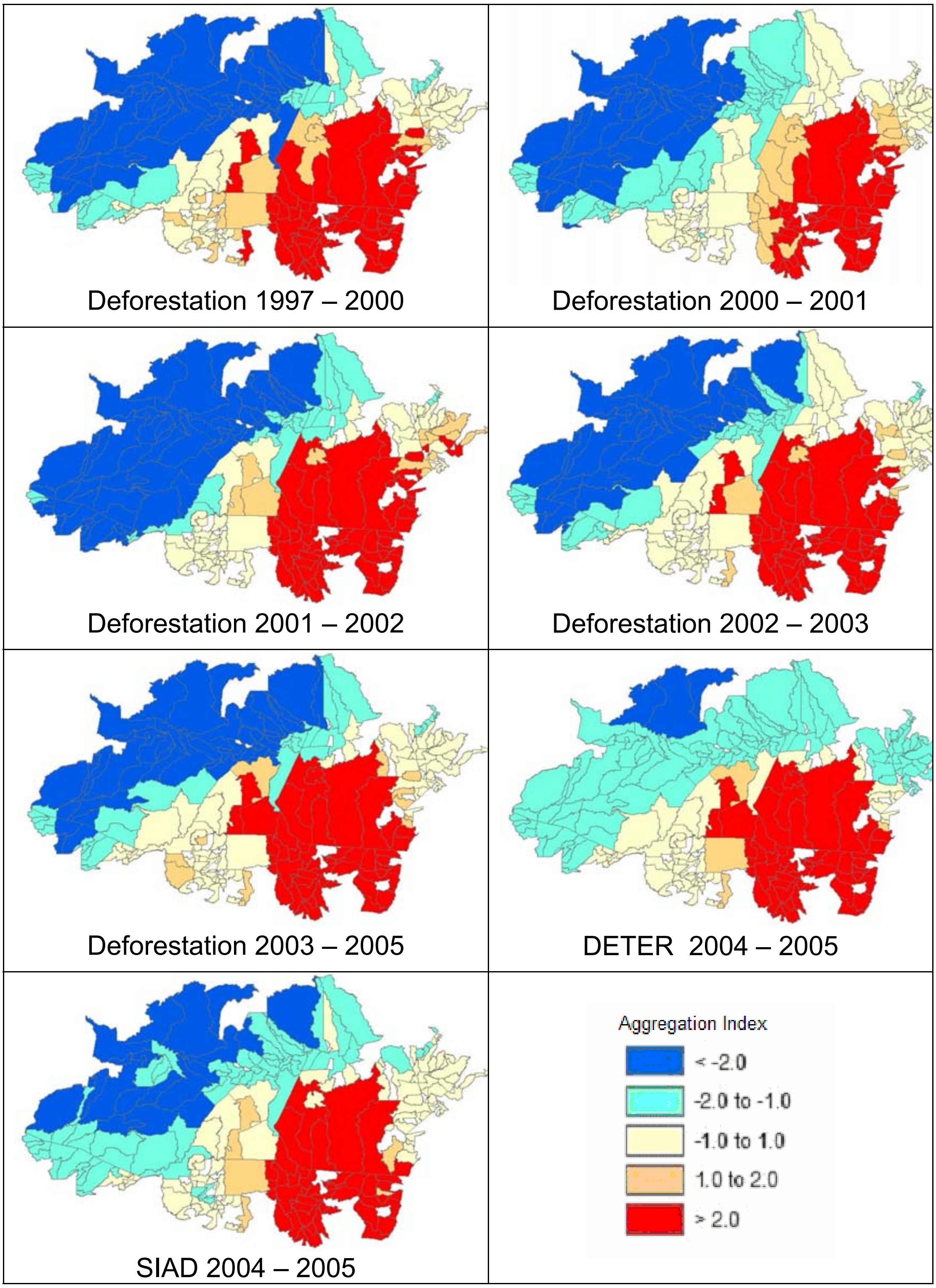

Figure 8 – Deforestation hotspot maps, where the municipalities with values equal or greater than 2 (in red) are classified as hotspots, while municipalities with values equal or smaller than -2 (in blue) are classified as coldspots

Table 3 – Linear regression results between the land concentration (x) and deforestation (y) hotspot G_i cluster values

Period	Model (y = ax + b)	r^2
1997 – 2000	y = 0.7724x + 0.3835	0.7188
2000 – 2001	y = 0.6989x + 0.16	0.7874
2001 – 2002	y = 0.9826x + 0.3792	0.8572
2002 – 2003	y = 0.7095x + 0.248	0.8029
2003 – 2004	y = 0.7454x + 0.2903	0.7341
2004–2005 DETER	y = 0.6509x + 0.2372	0.6753
2004-2005 SIAD	y = 0.8024x + 0.2422	0.7591

The results depicted in Table 3 indicate a strong correlation between land concentration and deforestation; i.e. areas with high land concentration are also likely to be more severely affected by deforestation.

Indeed, 48% of the deforestation detected in the study area for the period between 2000 and 2004, took place in 42 municipalities with hotspot aggregation index equal or greater than 2, while 75.8% of the deforestation were concentrated in the 94 municipalities with aggregation indices equal or greater than -1 (Table 4).

Table 4 – Deforestation % according to the hotspot G_i aggregation indices

	Index >= 2 (42 Municipalities)	Index >= -1 (94 Municipalities)
2000	40% of the deforestation	70% of the deforestation
2001	50% of the deforestation	73% of the deforestation
2002	55% of the deforestation	84% of the deforestation
2003	49% of the deforestation	76% of the deforestation
2004	46% of the deforestation	76% of the deforestation
μ	48% of the deforestation	75,8% of the deforestation
σ	± 5.52%	± 5.21%

The deforestation and land concentration hotspots are strongly correlated to each other (Figures 7 and 8), as well as to the agricultural revenue hotspots (Figure 9). In other words, deforestation tends to be more prominent in rather productive and concentrated ownership regions.

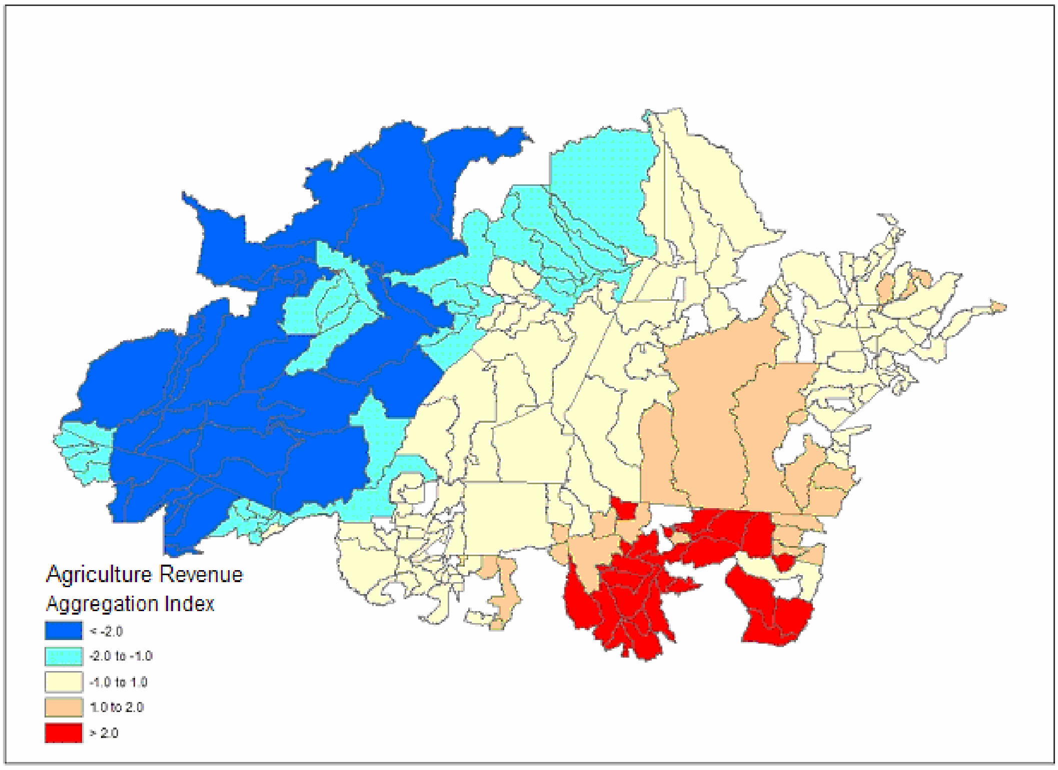

Figure 9 – Agricultural revenue hotspot map, where the municipalities with values equal or greater than 2 (in red) are classified as hotspots, while the municipalities with values equal or smaller than -2 (in blue) are classified as coldspots

5.5 Governance

Figure 10 shows the IBAMA hotspot map. Overall, the IBAMA hotspots (area in red in the map of Figure 10), comprise 57 municipalities, which are responsible for only 2.05% of the deforestation occurring each year in the study area.

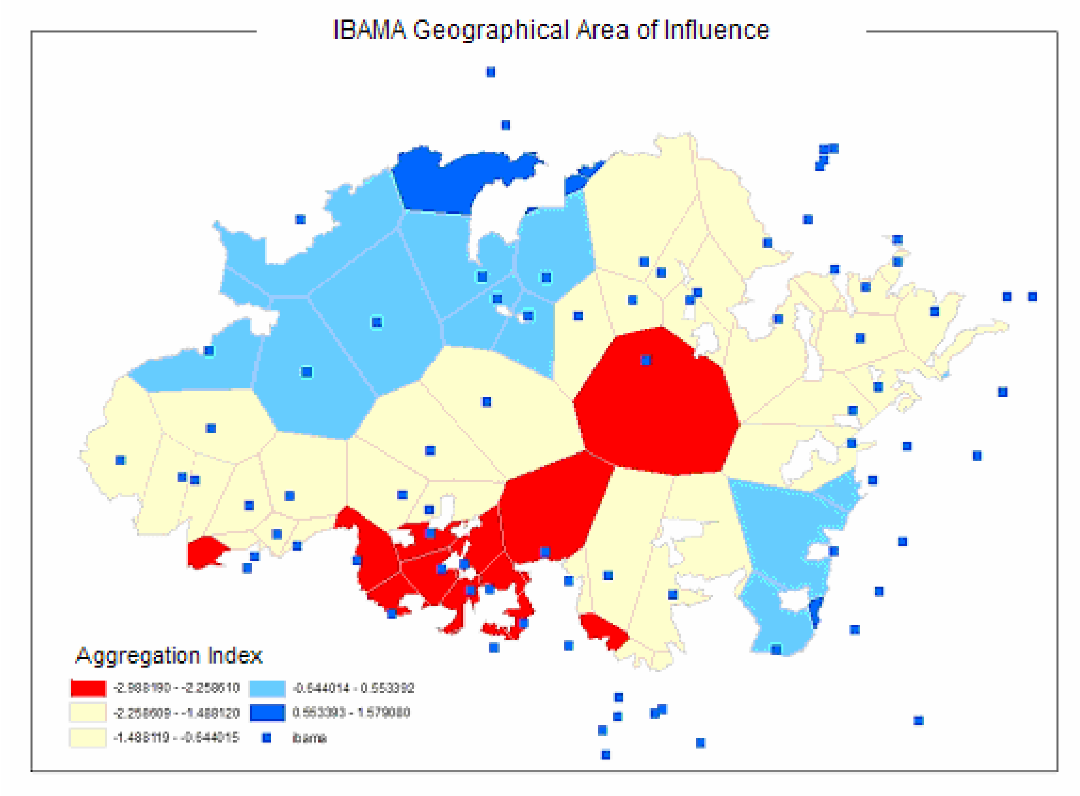

Figure 10 – Hotspot map depicting the region of influence of the IBAMA in the area of study. Polygons with values equal or smaller than -2 (in red) are classified as hotspots, while the polygons with values equal or greater than 0.5 (in blue) are classified as coldspots

In relation to the INCRA offices, it was not possible to derive a hotspot map, as their locations are restricted to the State capitals. Alternatively, in Figure 11, each INCRA office is located over the land concentration hotspot map. The hotspot map of the SIPAM communication terminals, which play a key role in the institutional integration and represents the overall governance existent in the region, is shown in Figure 12. As observed with the IBAMA and INCRA offices, the hotspot map of the SIPAM communication terminals is poorly correlated to the deforestation and land concentration hotspot maps.

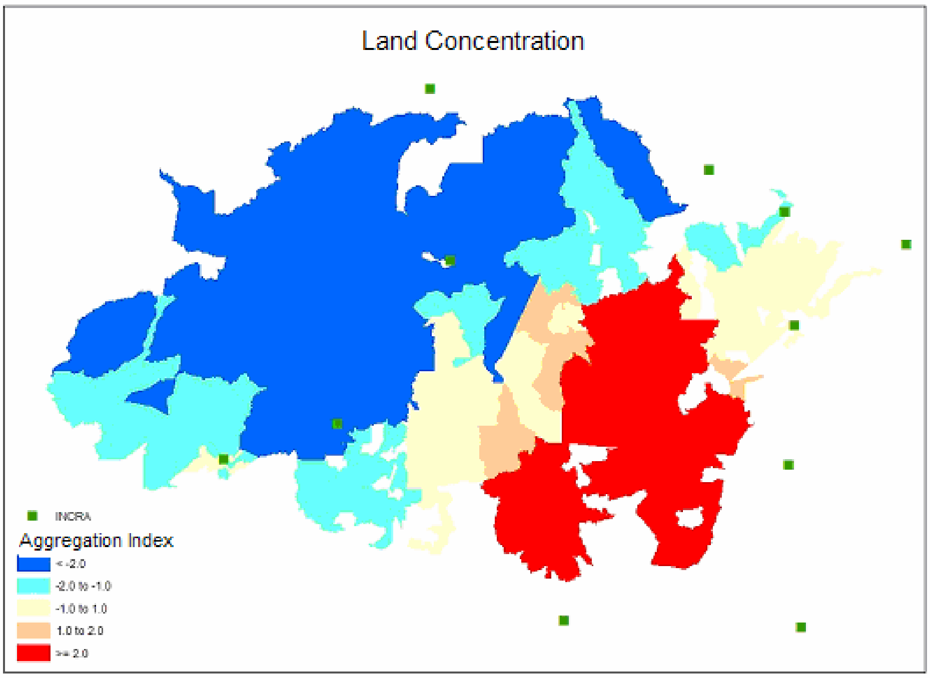

Figure 11 – INCRA offices (green squares) located relatively to the land concentration hotspot map

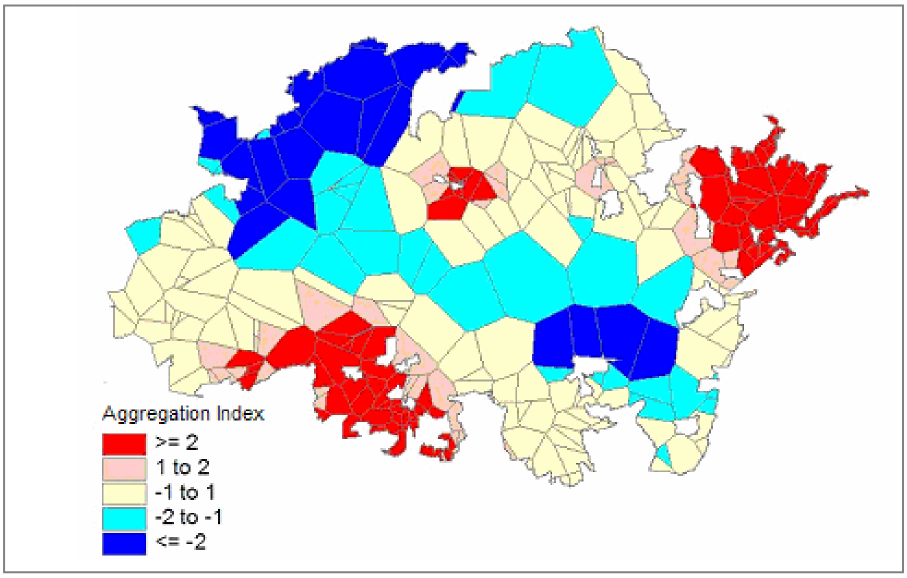

Figure 12 – Hotspot map of the SIPAM communication network. Polygons with values equal or greater than 2 (in red) are classified as hotspots, while the polygons with values equal or greater than -2 (in blue) are classified as coldspots

6. Concluding Remarks

In this paper, we evaluated remotely sensed deforestation data with respect to their social-economical and institutional context. According to our results, clearcutting in the Amazon forest is strongly correlated to land use (mainly cultivated pastures), as well as to appropriated land and land concentration. In fact, 48% of the land conversions in the study area until 2004 have occurred in the 42 municipalities with the largest land concentration aggregation values (i.e. hotspots indices). Likewise, linear regression results, considering the land concentration and deforestation values inside the hotspots, indicated that up to 80% of the deforestation can be well explained by the variation in land concentration.

Thus, regions with agrarian situation dominated by large properties are more prone to further conversions. In addition, land concentration is also closely correlated to rural conflicts (Martins, 1996). Indeed, in 2004, according to the Catholic Church Land Pastoral Commission, 118 conflicts and disputes (threatens to life, violation of human rights, attempted murders, etc), including 26 deaths and involving 13,398 families of land occupants, were registered in the area of study (CPT, 2004).

On the other hand, the majority of the development projects carried out in the Amazon systematically oversees the role of the agrarian structure, which is a mandatory issue concerning deforestation monitoring, environmental licensing of rural properties, and regional territorial planning and ordainment.

In relation to the presence of the state, a primary requisite for the proper organization of the territory, forest preservation, and reduction of the violence, this is still highly variable, and in most cases, insufficient. For instance, the INCRA, the government branch in charge of implementing the agrarian reform, has its presence in the study area restricted to the State capitals.

In relation to the IBAMA, the Brazilian federal environmental agency, its main area of influence correspond to 57 municipalities, where annual deforestation is only about 2.05% of the total amount occurring in the entire study area. In order to circumvent this geographical limitation, the IBAMA carries out every year huge fiscalization operations with the use of cars, helicopters, planes, etc. A more feasible and efficient alternative would be to redistribute its offices, allocating them according to the deforestation hotspots.

Another aspect to be considered, of social dimension, regards the eviction of small farmers and occupants due to the appropriation of their lands by large landholders. With this respect, it is extremely important that both the government and non-governmental organizations promote specific measures in order to assure thousands of families their right to the land. Such efforts may significantly contribute to reduce deforestation, as well as to minimize the serious social problems in the urban areas in Brazil.

It is also worthwhile to emphasize the role of territorial planning for a more sustainable land use and occupation in the Amazon. In fact, the severe clearcutting detected by satellite imagery evidences the lack of institutional integration, through the sharing of data and information, and the absence of territorial policies and governance.

Acknowledgments

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APÊNDICE 3

Assessing the response of the MODIS vegetation indices to landscape disturbance in the forested areas of the legal Brazilian Amazon.

Assessing the response of the MODIS vegetation indices to landscape disturbance in the forested areas of the legal Brazilian Amazon*

Nilson Clementino Ferreira [a]
Laerte Guimarães Ferreira [a]
Alfredo Ramon Huete [b]

[a] Federal University of Goias - UFG
Social and Environmental Studies Institute - IESA
Campus Samambaia - Cx. Postal 131 CEP: 74001-970 Goiania, GO, Brazil
E-mails: ncferreira@uol.com.br, laerte@iesa.ufg.br,

[b] Department of Soil, Water, and Environmental Science
University of Arizona, Tucson, AZ 85721, USA
E-mail: ahuete@ag.arizona.edu

Abstract

In this study, we assessed, by remote sensing means, the impacts of forest fragmentation on the Amazon landscape. Landscape disturbance, obtained for an area of approximately 3.5 million Km^2 through simple spatial metrics (i.e. number of fragments, mean fragment area, and border size) and principal component transformation were then compared to the MODIS NDVI (normalized difference vegetation index) and EVI (enhanced vegetation index) seasonal responses. As expected, higher disturbance values prevail in the southern border of the Amazon, near the intensively converted deforestation arc, and close to the major roads. Concerning the respective VI responses, the NDVI seasonal contrast tends to more closely follow the human-induced patterns; i.e. forest remnants from areas more intensively converted are

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usually associated with higher NDVI seasonal values. In fact, the significant correlation between the NDVI seasonal responses and landscape disturbances are clearly corroborated by the analysis of Geographically Weighted Regression (GWR) parameters and predictions. On the other hand, the EVI seasonality seems to behave more independently, and even in an opposite manner; i.e. higher variations tends to predominate over less fragmented forest patches. Although further research is needed, our results suggest that the degree of fragmentation of the forest remnants do contribute to the optical remote sensing signal. Thus, it may become possible the upscaling of field-based data on overall canopy condition and fragmentation status for basin wide extrapolations.

Keywords: Landscape ecology; Landscape disturbance; Forest remnants; MODIS VIs

1 Introduction

The pace and dimensions of global environmental changes, particularly after the second half of the XX century, have reached dramatic levels of impact whatsoever, affecting in an unprecedent manner the biogeochemical systems sustaining the biosphere (Lambin et al., 2001). Land use and land cover changes are among the most significant modifications, which acquire even greater importance in the tropics, where most of the biodiversity is concentrated. In fact, land cover change in the tropics implies in severe loss of biodiversity at global scales (Turner, 1997).

Due to the substantial progress in remote sensing technology and science, systematic deforestation mapping, especially in the Brazilian Amazon basin, has been conducted since 1978 (Skole and Tucker, 1993, INPE, 2000; Ferreira et al., 2006). Likewise, great deals of effort have been made in order to understand the causes, regarding social, economical, and institutional aspects, and trends of deforestation (Pfaff, 1999; Alves et al., 2003; Ferreira et al, 2006a).

In the Amazon, the conversion of forest to agriculture and pasture areas is being accompanied by intensive habitat fragmentation, which, besides alterations in their biological diversity and composition, is also responsible for considerable changes in ecological processes, such as nutrient cycle and polinization (Lovejoy *et al.*, 1986; Laurence and Bierregaard, 1997). In addition, forest fragments are more prone to tree mortality and canopy damages, apparently caused by micro-climatic changes and increased wind turbulence near their borders (Laurence et al., 1997). It is also important to consider the direct human induced impacts, as access to the forested areas is facilitated. Among others, these include selective logging, an augment in fire occurrences, intensive use of agricultural insums and defensives close to the fragment borders, and the hunting and introduction of endangered and exotic species, respectively.

In face to all these potential perturbations, the possibility of remotely assessing the conditions of the forest remnants is certainly instrumental in preserving the long term functioning of the ecosystems as a whole. In fact, some studies do suggest a strong correlation between forest structure and optical vegetation indices (Gamon et al., 1995; Oliveira-Filho and Fonte, 2000;

Freitas et al., 2005).

This paper, centered on the hypothesis that the optical remote sensing signal is affected by and respond to different levels of forest fragmentation, investigate, at the landscape scale, the current disturbance of the Amazon forest and how sensitive the MODIS vegetation indices are to these human-induced forest structures.

2 Experimental Design

2.1 Study Area

This study is focused on the tropical forest areas of the legal Brazilian Amazon. Specifically, this study is based on 3,5 million km^2 of forested areas (~ 87% of the entire Amazon basin), as 500.000 km^2 of forest, in the northern portion of the Amazon, were not considered, due to persistent cloud contamination (figure 1).

The area of study encompasses 332 (or 43,6%) municipalities of the legal Brazilian Amazon, inhabited by a total population of 9.698.797 people, from which, about 65% are found in urban areas (IBGE)[6].

In relation to deforestation, approximately 100% of the land conversion mapped by the PRODES initiative (INPE, 2003) occurs within the selected study area. In figure 2, it is possible to observe the increase in converted area, from 1997 to 2004, when 10.44% of all the forested area had already been converted into agricultural fields and cattle ranching.

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[6] www.ibge.gov.br

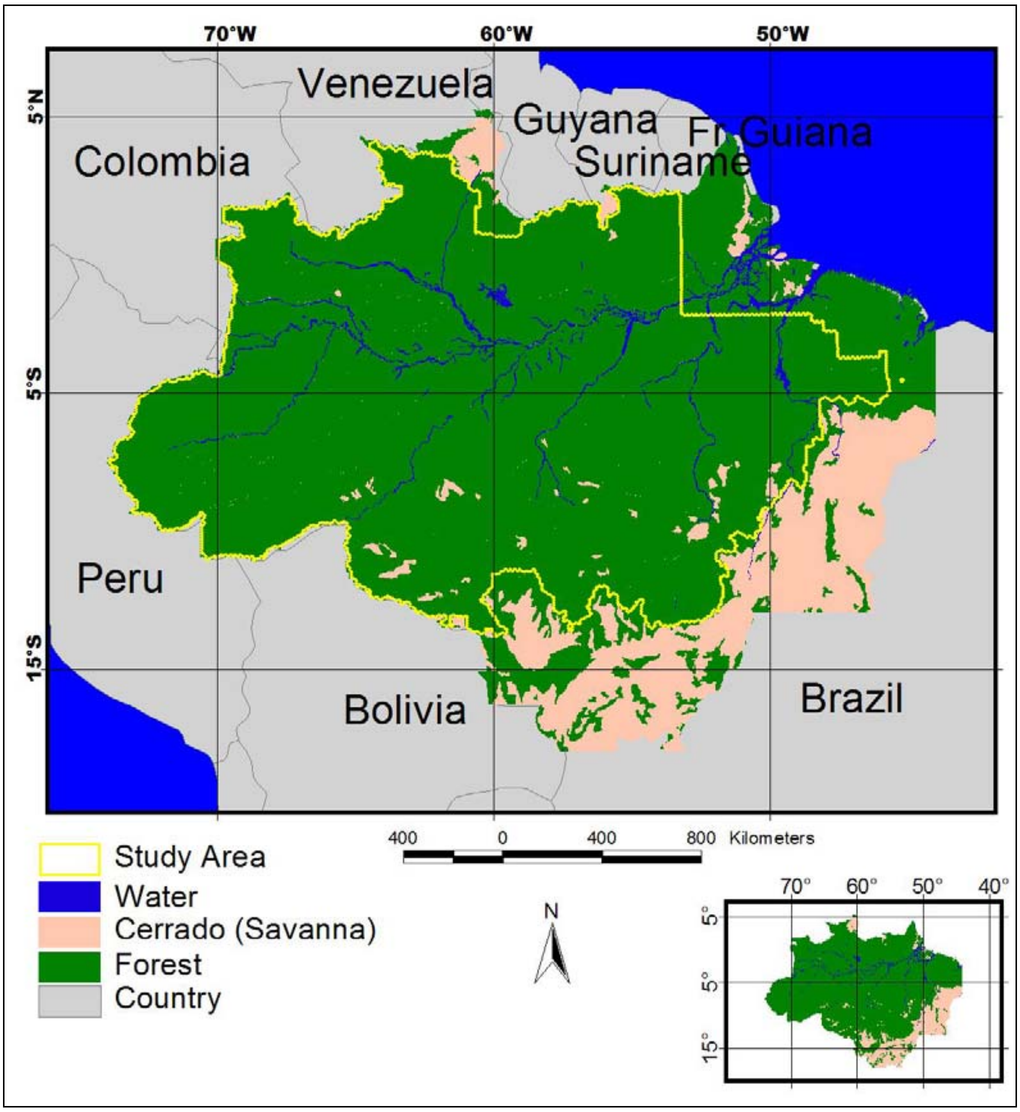

Figure 1 – Study site (yellow polygon), comprising about 3.5 million Km^2 of primary forest areas

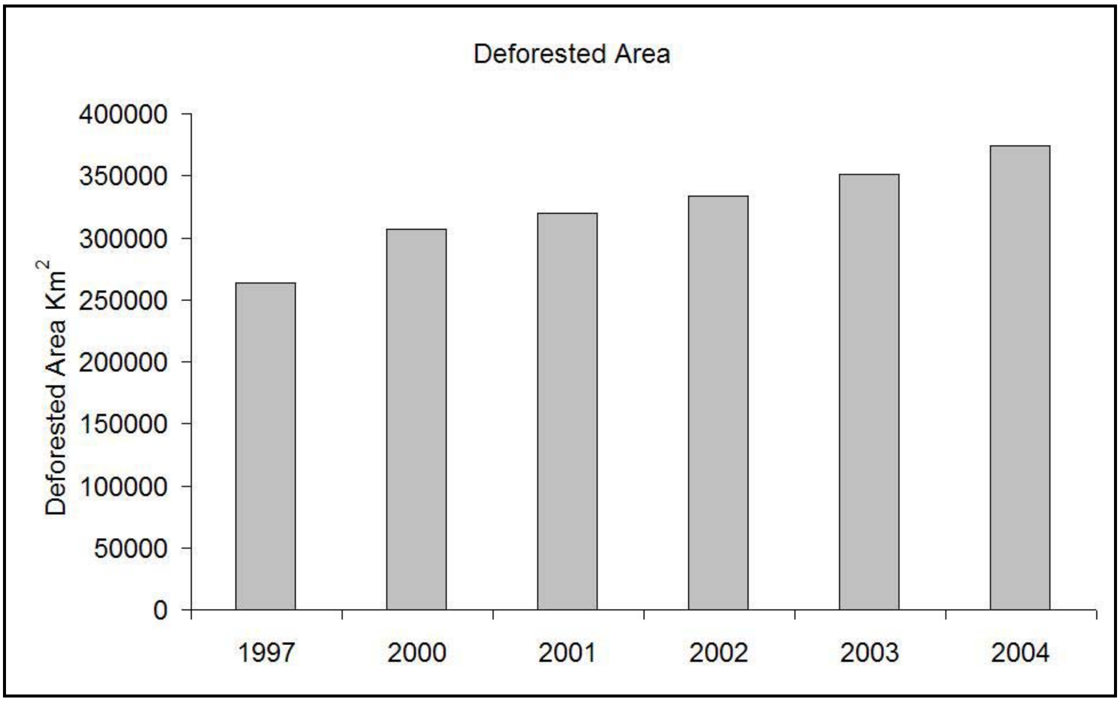

Figure 2 – PRODES deforestation detections, from 1997 to 2004, showing an average annual deforestation rate of 0.45%.

2.2 Dataset Description

This study, is primarily based on the PRODES data (Deforestation Monitoring Program) and MOD13Q1 imagery. The PRODES datasets, produced by the Brazilian Institute of Space Research (INPE), based on automated and visual interpretation of Landsat derived fraction images, is made available in vector format for the year 1997 and from 2000 to 2004. (Shimabukuro et al., 2000).

Regarding the MOD13Q1 product, eight tiles were necessary in order to cover the entire area of study (figure 3), from which we utilized both the enhanced vegetation index (EVI) and the normalized difference vegetation index (NDVI), as well as the accompanying quality assurance information band (Huete et al., 2002).

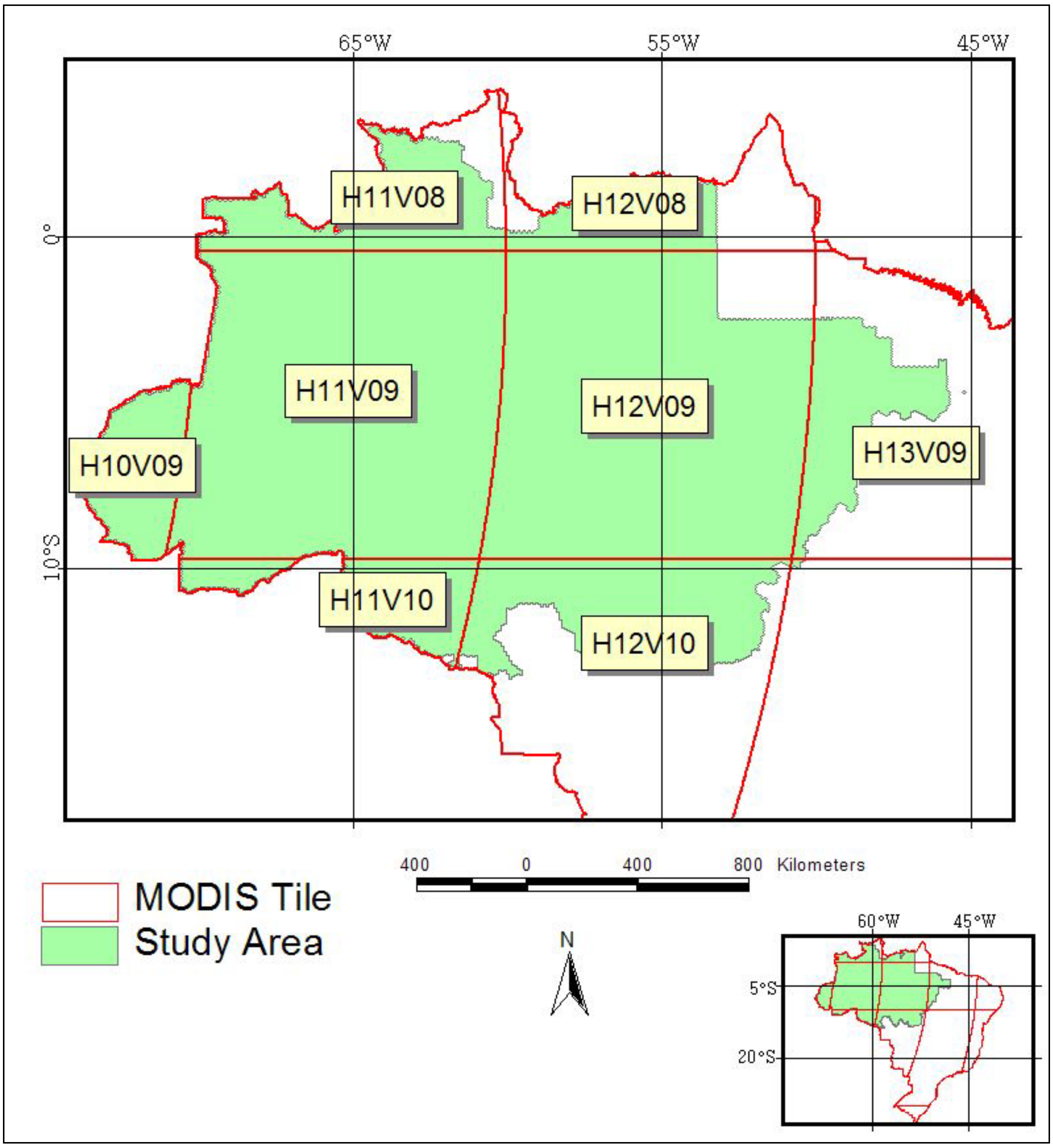

Figura 3 – MODIS Tiles (red polygons) over the study area (green polygon)

Due to the observed seasonality of the Amazon forest (Huete et al., 2006) and its possible effects in strengthening forest disturbances "signals", MODIS data, from 2005, were acquired for two distinct periods of time. The first period comprises the months of May and June, when most of the vegetative cover is still under the influence of heavy precipitation. A second time frame chosen was September, characterized by lower pluviometric activity, especially in the southern portion of the Amazon.

In order to minimize atmospheric contamination, we considered both Terra and Aqua MOD13Q1 data, which were thoroughly screened for residual clouds, shadows, and aerosol, and selected, on a pixel per pixel basis according to the maximum NDVI value. The filtered and reprojected mosaicks (from the sinusoidal projection to the geographical coordinate system) were then adjusted to the geographical limits of the area of study and the deforested pixels eliminated based on the PRODES data for 2004 or threshold values (i.e. pixel with NDVI values lower than 0.6). Likewise, pixels coincident with water bodies were discarded based on cartographic data.

All the processing flow described above with respect to the data utilized in this study is shown in detail in figure 4.

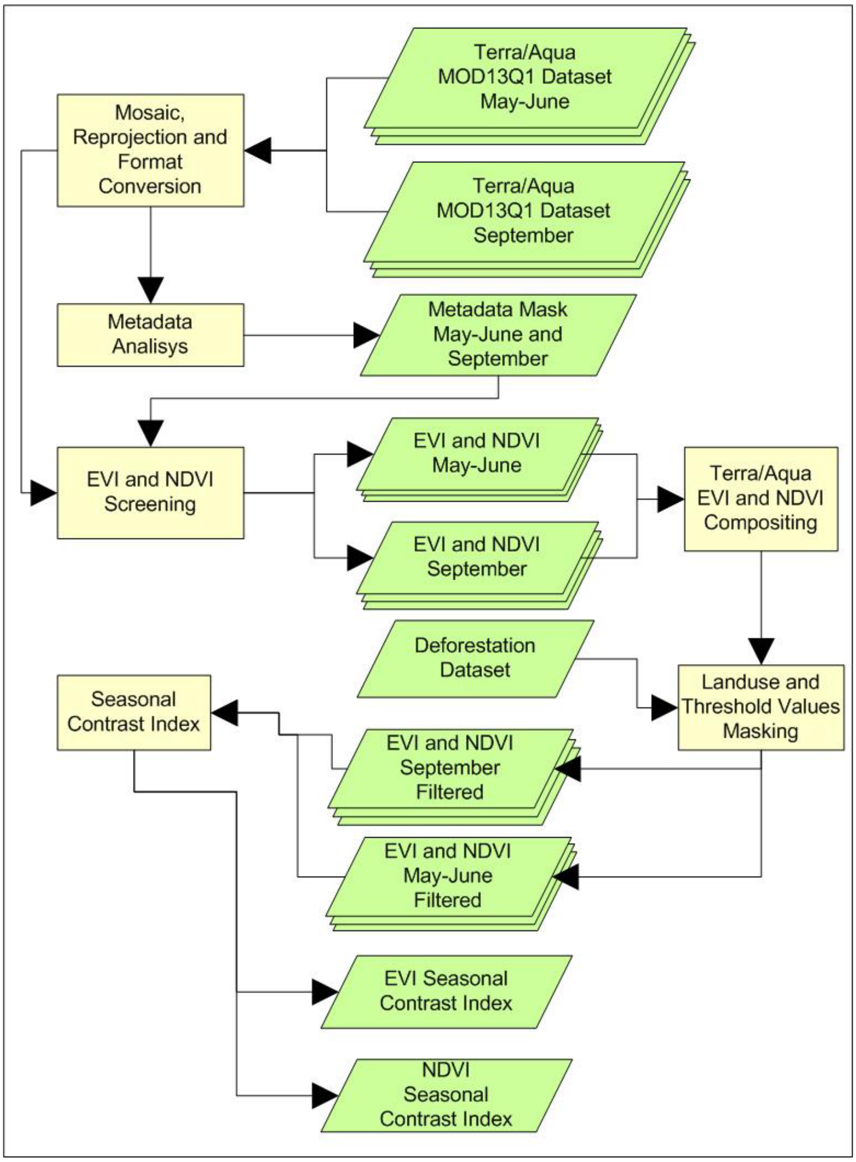

Figure 4 – Flow chart depicting the major steps concerning the acquisition and processing of the data utilized in this study.

2.3 Data Analysis

Data analysis consisted of different approaches. First, a regular hexagonal grid, comprising 35810 cells, of 10000 ha each (or 1600 250m resolution pixels), was geographically positioned over the study area (figure 5). However, only 28.242 hexagonal cells were utilized, as those with less than 60 pixels of remaining vegetation, or intercepting major rivers, were not considered.

Assuming each cell as a sampling unit, we obtained the respective landscape metrics (number of remaining forest fragments, mean fragment area, and amount of fragment border), calculated the EVI and NDVI seasonal contrast (eq. 1), and normalized all values as follow (eq. 2):

$$VI\ Seasonal\ Index = \frac{VI(May, June) - VI(September)}{VI(May, June)} \times 100 \qquad [1]$$

Where:

VI Seasonal Index – MODIS VIs (EVI, NDVI) seasonal responses

VI (May, June) – Vegetation index (EVI or NDVI) for the May / June period

VI (September) – Vegetation index (EVI or NDVI) for the September period

$$Normalized\ Value = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \times 10000 \qquad [2]$$

where:

Normalized Values – Normalized values for each sampling unit;

X – VI (EVI, NDVI) or landscape metric values for a given sampling unit;

X_{min} – Minimum X value among all the sampling units in the hexagonal grid ;

X_{max} – Maximum X value among all the sampling units in the hexagonal grid.

The landscape metrics resulted in three 250m resolution images, which were combined into a single “disturbance image” via a principal component transformation.

The response of the MODIS vegetation indices to the disturbance of the landscape was assessed through profiles along regional transects or around major roads, as well as based on regression analysis. Due to the large extension of the study area and the large number of sampling units, whose variables present continuum local variations, we opted, in addition to the regular regression models, to perform a geographically weighted regression (GWR) (Fotheringham et al., 1997), in which the dependent and independent variables (i.e. the VI seasonal contrast and the landscape disturbance, respectively) are locally adjusted (regressed) against each other.

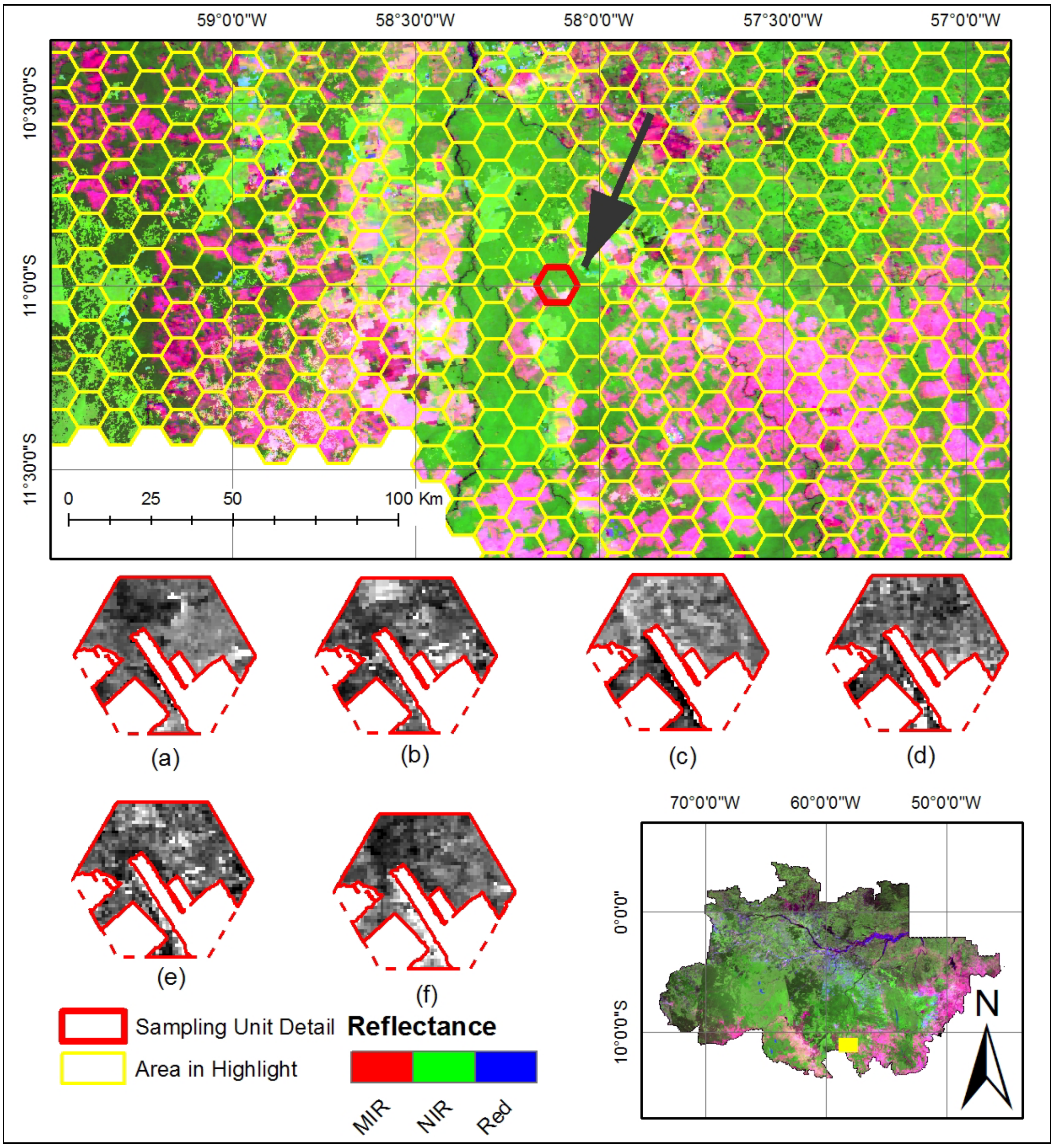

Figure 5 – Detail of the hexagonal grid positioned over the study area. For the highlighted cell (in red) it is shown the respective set of VI images utilized in this study: : a- NDVI May/June, b- EVI May/June, c- NDVI September, d-EVI September e- EVI Seasonal Contrast, f- NDVI Seasonal Contrast. Note that the blanket portion in each hexagon correspond to the “masked out” deforested areas.

3 Results and Discussions

3.1 Amazon Landscape Disturbance

Figure 6 shows the disturbance image, obtained through the principal component transformation of the three landscape metrics considered in this study (i.e. number of fragments, mean fragment area, and border size). Overall, the Amazon landscapes are still well preserved, with major disturbances restricted to their southern portions, along the so called deforestation arc (Nepstad et al., 1994).

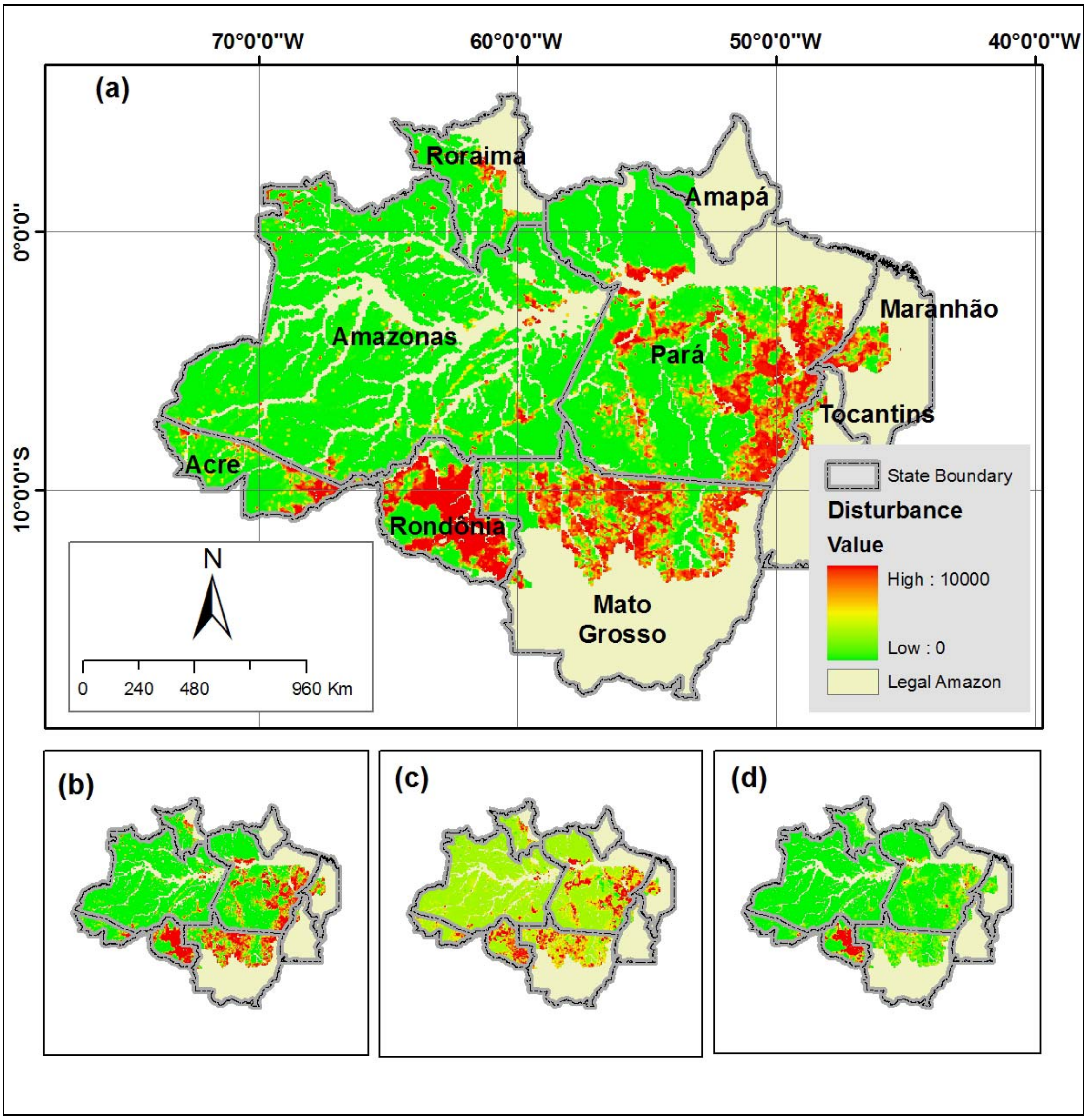

Figure 6 – (a) disturbance landscape map (first principal component image), where the shades of green indicate little or none disturbance, while the shades of red correspond to those areas highly disturbed; figures (b), (c), and (d) detail each landscape metric used (mean area, border size, and fragment number, respectively), where the shades of green are related to larger (and fewer) fragments, characterized by smaller borders, while the shades of red correspond to more abundant fragments, of smaller size and larger borders.

Considering the role played by road system on deforestation, as demonstrated by different studies (e.g. Ferreira et al., 2006b), landscape disturbance was also assessed in relation to five important roads (BR174, PA150, BR230, BR163, and BR364), amounting 6,700 km in length, 49% of which are paved (figure 7).

Based on these roads, and on a set of buffers placed around them, at 0-10, 10-20, and 20-30 kilometers, disturbance data, from 3082 hexagons were extracted and evaluated on an average basis. As expected, each road presents a distinct disturbance profile, which decreases the further the location is in relation to a given road. Likewise, higher values are predominantly found for those roads crossing (BR 163) or along (BR 364 and PA 150) the deforestation arc. By contrast, the BR 230, known as Transamazon and aimed at fostering the regional integration of less developed areas, and the BR 174, situated north of the Amazon river (a natural barrier to development approaching from the South) and serving the isolated and extrativist (e.g. rubber) state of Roraima, present disturbance values below 0.4 and as low as 0,1.

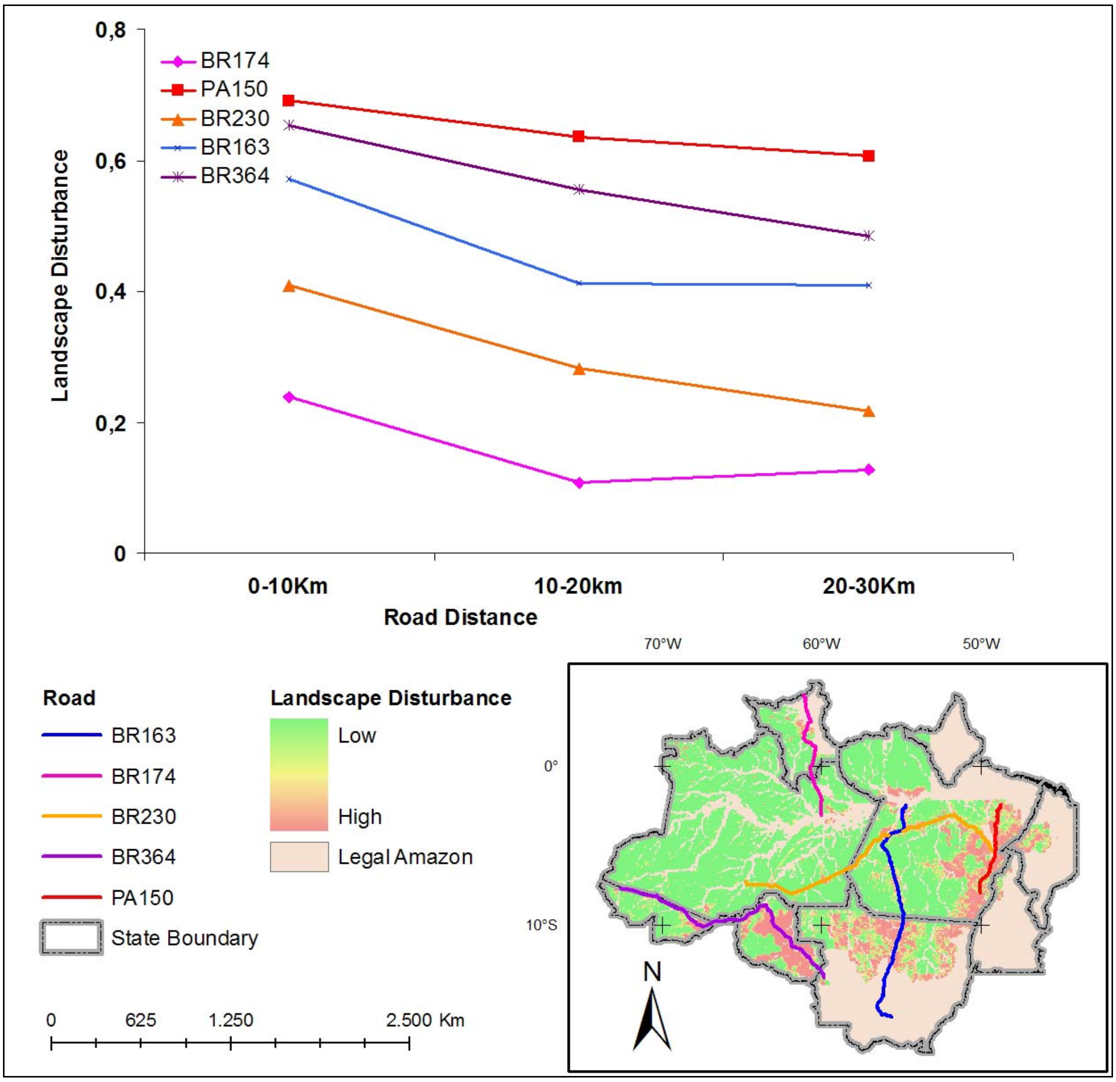

Figure 7 – Landscape disturbance profiles around major Amazon roads

3.2 VI Responses

Figure 8 shows a north-south transect over the landscape disturbance image, along which seasonal VI and disturbance data profiles were extracted.

As observed before, high disturbance values are found in the southern region, where the transect intercepts the deforestation arc. Regarding the corresponding VI responses, while the NDVI tends to more closely follow the disturbance pattern, with higher seasonal contrast values near the deforestation arc, the EVI seems to behave more independently. The differences observed between the EVI and NDVI profiles are very likely related to the well documented differences in the behavior of these two indices (e.g. Ferreira et al., 2004). i.e. over pristine areas, as those predominating in the upper portion of the transect, the EVI, more sensitive to the chlorophyll content and canopy structure, is highly responsive, to both seasonality and structural variations. As opposed, over such areas, the NDVI, more prone to saturation, tends to show smaller variations in both the spatial and temporal domains.

On the other hand, the ready response of the NDVI to the more intensively disturbed fragments, as those found in the deforestation arc, seems to be directly related to background variations, as these fragments are more susceptible to seasonal differences in the moisture content and droughts effects. By contrast, the EVI, specifically designed to accommodate such background variations, yields smaller seasonal responses, more weakly coupled to the overall condition and fragmentation of the landscape.

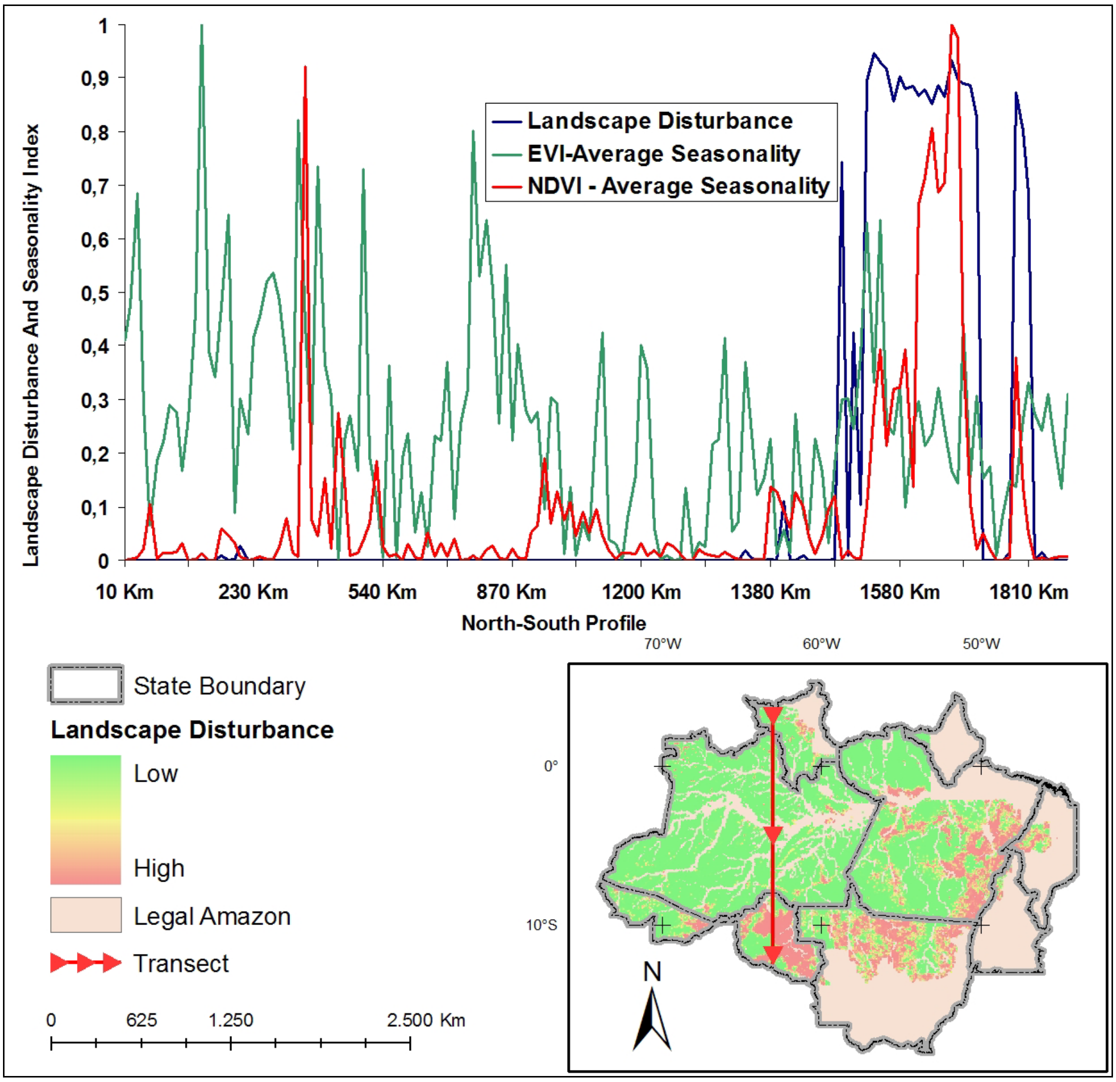

Figure 8 – Mean VI seasonal and ladscape disturbance profiles along a north-south transect

The apparent stronger correlation between NDVI seasonal variation and landscape disturbance is corroborated by the regression results shown in figure 9. Is interesting to observe that these regressions based on a 30 km buffer around the five roads depicted in the figure 7, show an opposite behavior between the EVI and the NDVI fitted models. While the NDVI based model shows an upward trend and a strong goodness of fit coefficient (i.e. 0.81), the EVI is associated to a downward curve and a much weaker coefficient (i.e. 0.35). In other words, the higher the disturbance of the landscape, higher is the variation in the NDVI seasonal response. By contrast very little of the EVI seasonal variations is accounted by the disturbances of the landscape.

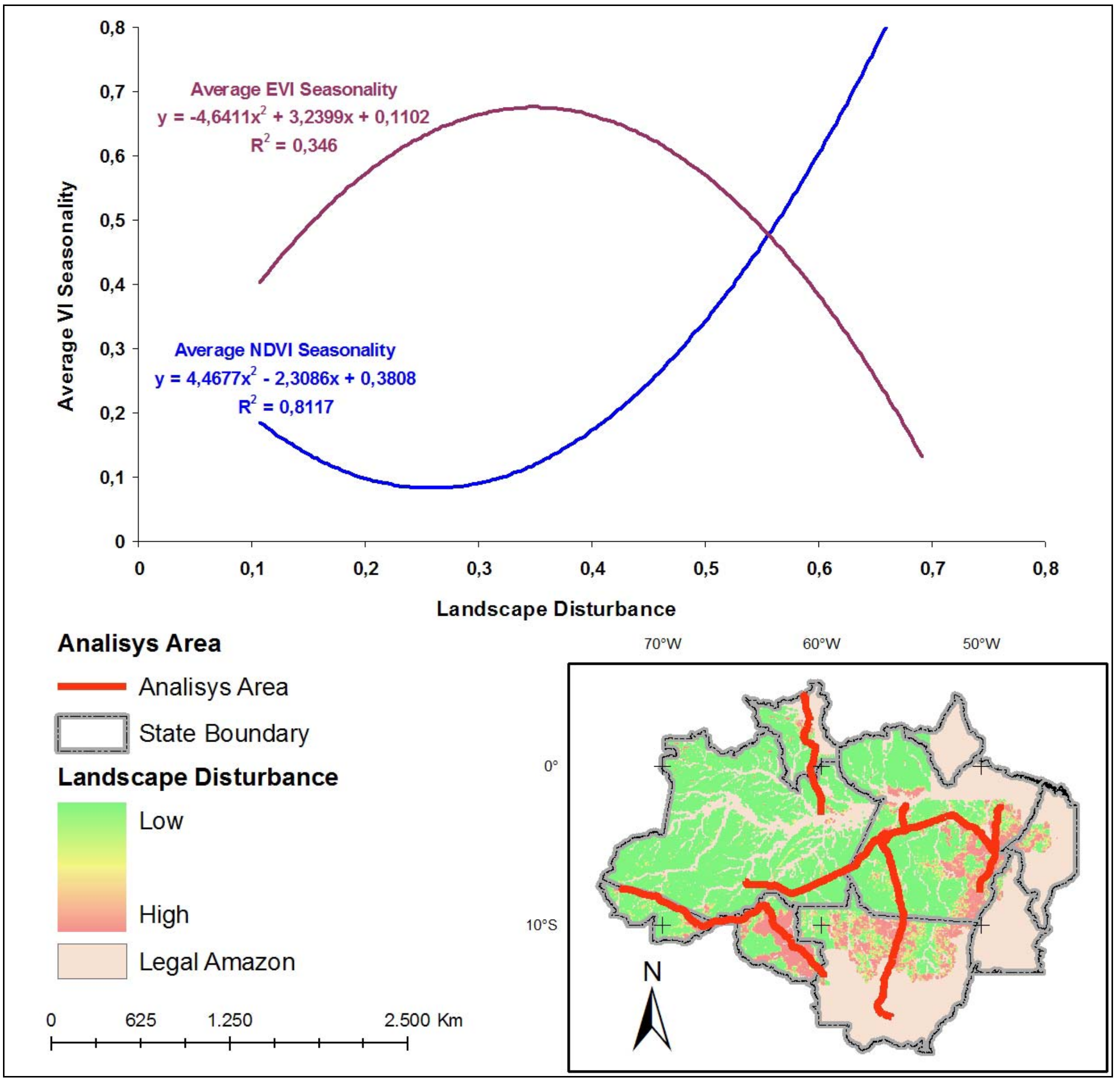

Figure 9 – Regression analysis between landscape disturbance and the NDVI seasonal responses within a 30 Km buffer from five major Amazon roads

3.3 GWR Analysis

The NDVI seasonal response dependence on the landscape disturbance was further investigated, regarding its spatial context, at both the local and regional scales via the GWR model. Overall, variations in the landscape disturbance explain about 62% of the variations encountered in the NDVI seasonal values. Likewise, a quite similar distribution pattern can be observed between predicted and true NDVI seasonal values.

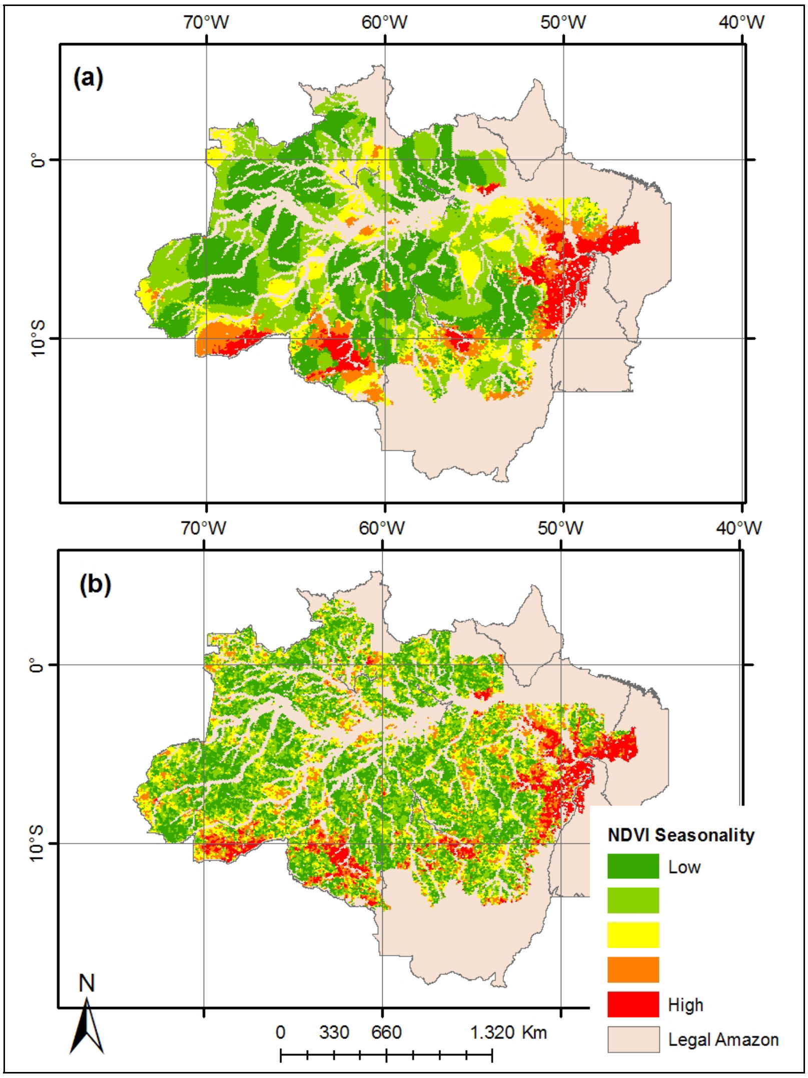

Figure 10 – GWR predicted (a) and MODIS derived (b) NDVI seasonal responses

As seen in figure 11, for most of the study area the slope coefficients are significantly greater than zero, suggesting that the landscape disturbance does account for a substantial part of NDVI seasonal responses. Accordingly, the lowest p-values are predominantly distributed along the deforestation arc. On the other hand, large p-values, related to slopes not significantly different from zero, are mainly found in those areas of denser hydrographic network, where “spurious” contributions to the pixel (e.g. water, clouds, shadows, etc.) are likely to occur.

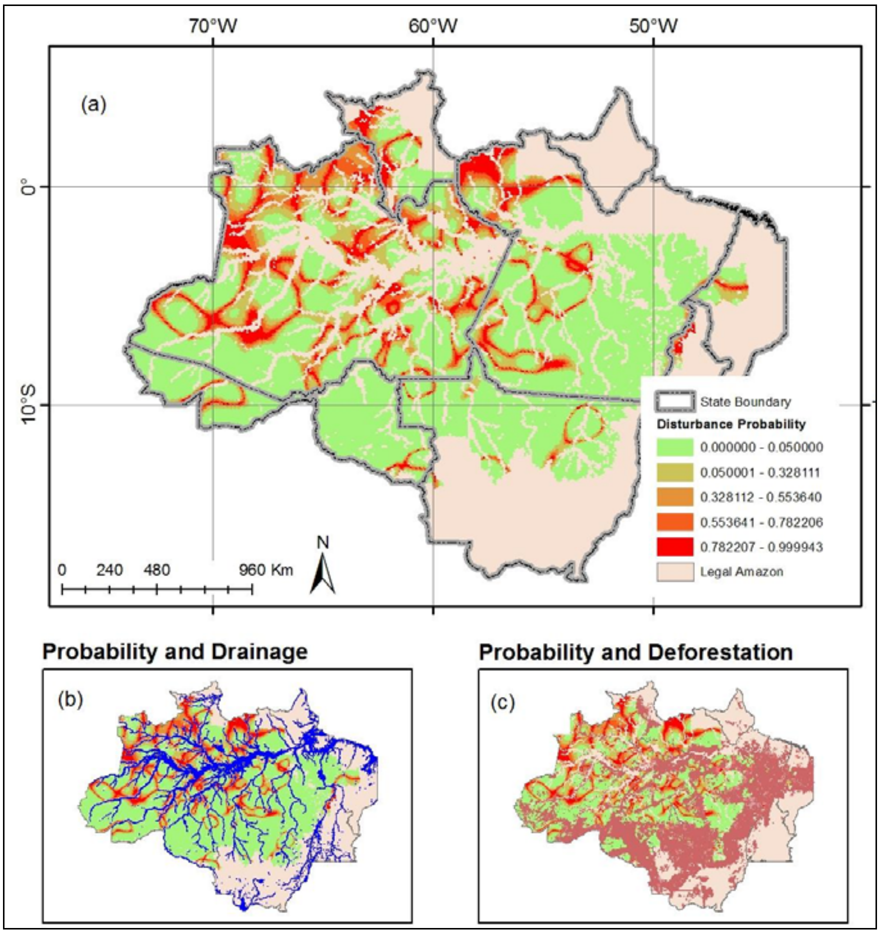

Figure 11 – Spatial distribution of the GWR slope (landscape disturbance) probability values (a) and their respective relations to the hydrographic network (b) and land conversion (c).

4. Concluding Remarks

In this study we attempted to understand how the fast pace deforestation in the legal Brazilian Amazon is impacting the landscape and how the MODIS vegetation indices respond to such disturbances.

In the pursuit of these goals, we considered an extensive area of 3,5 million Km2 and a massive dataset comprising both Terra and Aqua 2005 MODIS VI images for the May-June (predominantly wet season) and September (predominantly dry season) periods, from which only screened data over preserved forested areas were taken into account.

Based on an innovative sampling scheme comprising 28.242 regular hexagonal cells, forest disturbance was assessed according to simple landscape metrics (i.e. number of fragments, mean fragment area, and fragment border), combined into a single image, via a principal component transformation. As expected, higher disturbance values prevail in the southern border of the Amazon, near the intensively converted deforestation arc, and close to the major roads. Interestingly, each one of the five selected roads presents a distinct disturbance profile. For the three "arc of deforestation" roads, disturbance values, on a 0 to 1 scale, are, within a 30km buffer, above 0.4, while the roads located at denser and less fragmented forest patches are below 0,4 and as low as 0.1.

Concerning the respective VI responses, these were evaluated according to the seasonal contrast between the May/June and September EVI and NDVI values. As our results suggest, the NDVI seasonal contrast tends to more closely follow the human-induced patterns; i.e. forest remnants from areas more intensively converted are usually associated with higher NDVI seasonal values. In fact, the significant correlation between the NDVI seasonal responses and landscape disturbances are clearly corroborated by the GWR regression analysis and predictions. On the other hand, the EVI seasonality seems to behave more independently, and even in an opposite manner; i.e. higher variations tends to predominate over less fragmented areas.

Our results, though preliminary and not fully conclusive, do indicate the possibility of qualitatively and quantitatively assess, at the landscape scale and based on simple spatial metrics, the impacts of land conversion over the forest remnants. As clearly demonstrated, these impacts, expressed in terms of landscape fragmentation, do contribute to the remote sensing signal, and are particularly sensitive to the NDVI seasonal responses. To a certain extent, the findings of our study leave opened the possibility of large-scale extrapolations of field-based data on overall canopy condition and fragmentation status.

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