DEFORESTACIÓN Y CAMBIO EN LA COBERTURA DEL SUELO EN COLOMBIA: DINÁMICA ESPACIAL, FACTORES DE CAMBIO Y MODELAMIENTO

LAND-COVER AND LAND-USE CHANGE AND DEFORESTATION IN COLOMBIA: SPATIAL DYNAMICS, DRIVERS AND MODELLING

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RESUMEN

Esta tesis analiza el cambio en la cobertura y uso del suelo con énfasis en los procesos de deforestación en dos regiones contrastantes de Colombia: Andes y Guyana, entre 1985 y 2000. Se aplicó un enfoque espacial y temporal a partir de modelos de LULCC para evaluar y predecir los procesos de cambios asociándolos a variables explicativas y junto con métricas del paisaje y sistemas de información geográfica se analizaron patrones de deforestación.

La información de cobertura del suelo se baso en la interpretación de imágenes satelitales y las variables explicativas incluyeron datos biofísicos y socioeconómicos provenientes de una amplia gama de fuentes de información. Para la región de los Andes, el enfoque se dirigió a la aplicación de modelos de cambio de la tierra y de deforestación entre bosques montanos (montane forest) y bosques de piedemonte (lowland forest), usando enfoques espacialmente explícitos (Land Change Modeler-LCM) y modelos lineales generalizados (GLM) a los cuales se les asocio un conjunto de variables explicativas relacionadas con el proceso de cambio. A nivel de la región de la Guayana, se estudiaron los patrones de deforestación en los modelos de ocupación típicos de la región, comparando tasas de cambio, patrones del paisaje y efectividad de figuras de conservación. Finalmente se modelizo el potencial de cambio futuro en ambas regiones prediciendo su evolución e identificando zonas de alto riesgo de deforestación y sus implicaciones frente a la conservación de la biodiversidad.

Las tasas de deforestación varían entre las regiones y al interior de ellas. Para los Andes la tasa anual de deforestación fue de 1.41%, mientras que para Guayana de 0.25%; sin embargo en Guyana se evidenciaron las mayores tasas asociadas con una fase rápida e intermedia de pérdida de bosque en un modelo de transición de colono a establecimientos permanentes. Los modelos utilizados en esta tesis, sugiere que el modelo espacial de LCM basado en probabilidades de Markov tiene un mejor respuesta para explicar los cambios en el uso del suelo que los modelos lineales generalizados. La variable explicativa que mayor incide en los procesos de cambio de uso del suelo y deforestación es la distancia de las carreteras, pero existen variables como la actividad económica, pendiente, distancia a pastos y precipitación que impulsan procesos de cambio y el peso de estas variables depende del tipo de bosques y la región.

Los resultados de esta tesis mostraron que algunas figuras de protección como el sistema de parques naturales nacionales y los resguardos indígenas pueden ser efectivas para frenar procesos de deforestación y que las zonas de transición entre Andes y Amazonia, Orinoquia y Magdalena Medio se encuentran bajo una mayor amenaza de conversión probable debido a su accesibilidad y migración de la población. Finalmente, una mejor comprensión de la dinámica de LULCC en Colombia, es un paso importante en el desarrollo de estrategias de planificación del territorio y conservación de la región y las investigaciones futuras deberán evaluar la incidencia de las políticas nacionales tales como tenencia de la tierra, REDD, políticas sectoriales, económicas y energéticas ante cambios en el uso del suelo y la deforestación.

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INTRODUCCIÓN

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CAMBIO DEL USO Y COBERTURA DE LA TIERRA Y CAMBIO GLOBAL

La utilización del suelo es el resultado de la interacción de una serie de factores biofísicos, económicos, tecnológicos, institucionales, culturales, etc, que operan en un rango de escalas espaciales y temporales y se correlacionan con los procesos y patrones del paisaje. Dado que los cambios en el uso de la tierra son cada vez más rápidos, es necesario comprender las fuerzas que impulsan esos cambios y predecir sus efectos sobre los procesos del ecosistema o del ambiente global (Veldkamp & Lambin, 2001; Claessens *et al.,* 2009).

El cambio del uso y cobertura del suelo (LUCC por sus siglas en inglés), término usado para indicar las modificaciones que sobre la superficie terrestre ha realizado la actividad humana y/o las perturbaciones a través del tiempo, ha sido reconocido un elemento clave del cambio ambiental global. LUCC afecta el funcionamiento del ecosistema y es uno de los principales impulsores de la perdida de la diversidad biológica, fragmentación de hábitats y vulnerabilidad de los ecosistemas (Lambin *et al.,* 2003; Foley *et al.,* 2005; Chazal & Rounsevell, 2009; Manandhar *et al.,* 2010), contribuyendo entre el 15 -20 % en las emisiones de dióxido de carbono a nivel mundial (IPCC, 2000) e incidiendo en los cambios en el clima regional y mundial (Brovkin *et al.,* 2006). Se proyecta que para el año 2050 LUCC será el factor de mayor incidencia en la pérdida de la biodiversidad, seguido del cambio climático (Sala *et al.,* 2000). Por ello, su estudio se ha convertido en una de las principales prioridades de los investigadores de diferentes campos y los responsables de políticas ambientales frente a la conservación de la biodiversidad, la ordenación del territorio, la gestión de áreas protegidas y el análisis del cambio climático (Verburg *et al.,* 2005).

Las variaciones en la cobertura del suelo constituyen uno de los forzamientos naturales y antropogénicos que inciden en cambios climáticos a escala mundial, regional y local (IPCC, 2007) y que afectan procesos biogeoquímicos tales como emisiones de gases de efecto invernadero (CO_2 y CH_4) y biofísicos como la modificación del albedo de la superficie del suelo (Foley *et al.,* 2005; Feddema *et al.,* 2001; Brovkin *et al.,* 2006; Betts, 2005). Adicionalmente el cambio climático junto con cambios en LUCC reducen drásticamente la biodiversidad, al modificar los patrones de distribución de los ecosistemas, tamaño y estructura de la población, cambios en la distribución, composición e interacción de las especies, extinción global de especies endémicas, modificaciones en la frecuencia e intensidad del régimen de perturbaciones, entre otros (IPCC, 2002; CDB, 2009). Otros impactos ambientales de LUCC incluyen la alteración hidrológica regional y local debida a la construcción de represas, drenaje de humedales, etc, la contaminación del agua, suelo y aire. Finalmente, los cambios en la intensidad y los patrones espaciales de uso de la tierra afectan a la capacidad de los sistemas biológicos para apoyar las necesidades humanas y pueden llevar a la perdida de importantes servicios de los ecosistemas y a la provisión de las demandas futuras de nuestra sociedad (Lambin *et al.,* 2006; Quetier *et al.,* 2009).

En el ámbito global, los factores de mayor incidencia en los procesos de cambio de cobertura y uso del suelo están asociados con la *deforestación*. La conversión de bosques a otras cubiertas son procesos complejos que se producen con relativa rapidez y que dependen de varios factores. Específicamente, los bosques tropicales a pesar de cubrir menos del 10% de la superficie terrestre, representan la mayor diversidad biológica del planeta y son importantes para el ciclo global del carbono y la regulación hídrica (Mayaux *et al.,* 2005), contribuyendo el cambio del uso del suelo y la deforestación tropical con un alto porcentaje de las emisiones de CO_2 a nivel mundial (1.1 PgC yr−1 durante 1990s) y por consiguiente con problemas asociados al cambio global (Achard *et al.,* 2002; Santilli *et al.,* 2004).

LOS BOSQUES TROPICALES Y SUS FACTORES DE CAMBIO

Se estima que en el año 2000 existían 1571 millones de ha de bosques húmedos tropicales (FRA, 2000 Remote Sensing Survey) con un área deforestada de 5.7 millones de hectáreas al año y 2.3 millones afectadas por procesos de fragmentación, tala o incendios. El sudeste de Asia tiene la mayor tasa anual de deforestación (0.79) seguida de América Latina (0.51) y África (0.34), siendo la transición más evidente en el sudeste asiático (Mayaux *et al.,* 2005). Brasil e Indonesia representaban el 20,3% de la pérdida de bosques tropicales en 1980, el 25,7% de la pérdida durante la década de 1990, y el 40,7% de la pérdida entre 2000 y 2005 (FAO, 2006).

Los bosques tropicales sufren cambios rápidos de uso del suelo (Achard *et al.,* 2002) y han experimentando una expansión lenta de tierras de cultivos hasta el siglo XX con un aumento exponencial en los últimos 50 años (Ramankutty *et al.,* 2006). Estos cambios se asocian con fuerzas motrices subyacentes o indirectas (*Underlying* *driving forces*), que se han agrupado en factores biofísicos, económicos, tecnológicos, demográficos, institucionales y culturales, con y fuerzas de cambio próximas o directas (*Proximate causes*) que implican acciones sobre la cobertura de la tierra (expansión agrícola, extracción de madera, etc) y que generalmente operan a nivel local. Cambios en cualquiera de estas fuerzas producen cambios en uno o más de los factores inmediatos de LUCC (Geist *et al.,* 2006).

A nivel global, los factores de mayor incidencia en los procesos de cambio en el trópico generalmente se asocian con la expansión agrícola y ganadera, la extracción de madera, el establecimiento de plantaciones, la minería, la industria y el desarrollo de infraestructura urbana y vial, factores directos que causas procesos de deforestación (Geist & Lambin, 2002; Rudel, 2007). A nivel de América Latina, las características geográficas, los factores socio-económicos y los parámetros biofísicos son los impulsores directos de cambio de uso del suelo y en menor proporción la accesibilidad, el mercado y la densidad poblacional (Wassenaar *et al.,* 2007). En escalas más locales, el cambio está ligado a una combinación específica de factores biofísicos, económicos, tecnológicos, institucionales, culturales y demográficos y de historia del uso del suelo que depende de cada lugar y de cada contexto histórico (Geist & Lambin, 2002). Las causas subyacentes de LUCC en el trópico son a menudo exógenas a las comunidades locales que administran la tierra y, por lo tanto, difíciles de controlar.

Desde los años 80, se han hecho varios intentos para explicar las causas de los patrones de deforestación en el trópico (Geist & Lambin 2001), existiendo dos caminos divergentes: la causalidad debida a un solo factor generalmente asociado con el crecimiento poblacional frente a la complejidad de factores. A partir de un metanálisis de 227 estudios de deforestación tropical, Rudel *et al.,* (2009) identifica que en el periodo de 1960 a 1985 las fuerzas que impulsan la deforestación fueron de tipo social, donde los estados, mediante programas de colonización más una reforma agraria, estimularon la expansión agrícola de pequeños agricultores e impulsaron la construcción de carreteras y nuevos asentamientos de la población rural. Las tendencias desde 1985 hasta el presente dejan entrever la relevancia de la globalización y los mercados internacionales como impulsores de la deforestación, donde la presión de las poblaciones rurales sobre el recurso ha disminuido y las empresas privadas han comenzado a exportar grandes cantidades de soja y carne.

Por otra parte, la combinación de la expansión de las tierras de cultivo y la intensificación de la agricultura ha variado geográficamente. Mientras que Asia tropical ha aumentado su producción de alimentos mediante la utilización de fertilizantes y riego, la mayoría de países de África y América Latina han aumentado su producción a través de la intensificación agrícola y extensificación. Desde 2005, el aumento del uso de maíz, caña de azúcar, palma de aceite y biocombustibles derivados del petróleo han estimulado la generación de nuevos flujos de comercio internacional y nuevas presiones sobre los bosques y son los grupos privados los que han impulsado la construcción de nueva infraestructura (Rudel *et al.,* 2009). Otros impulsores de cambio en el trópico está asociados con patrones generales de tierras dedicadas a pastizales (África contiene un 26% del total de área a nivel mundial, Asia un 25%, y América Latina y el Caribe el 18%) y la urbanización asociada al crecimiento poblacional urbano en todo el mundo, afectando la huella ecológica de las zonas peri-urbanas (Ramankutty *et al.,* 2006).

Las tendencias a nivel mundial sugieren que los países más ricos de Europa y América seguirán un proceso de abandono de tierras agrícolas y forestación, mientras que países pobres de Asia, América y África seguirán con destrucción generalizada de los recursos y plantaciones en gran escala. Para las zonas tropicales Geist *et al.,* (2006) identificaron las transiciones de LUCC sintetizándolas en: urbanización, conversión de bosques en tierras de cultivo, conversión de pastizales en tierras de cultivo, uso más intensivo de las tierras de cultivo, incorporación de árboles en las tierras de cultivo, conversión de tierras de cultivo a bosques, conversión de bosques a pastizales, conversión de tierras de cultivo en pastos y uso más intensivo de los pastos. Pese a ello las transiciones deben ser vistas como posibles vías de desarrollo donde la dirección, el tamaño y la velocidad pueden orientar estrategias de manejo.

APROXIMACIONES PARA EVALUAR LUCC

Debido a la importancia del proceso LUCC, los científicos de diversas disciplinas han desarrollado conjuntamente metodologías para la detección de los cambios y la explicación de las causas subyacente de ese cambio, que van desde la aplicación de teledetección, análisis geoespacial y sistemas de información geográfica, hasta el desarrollo de modelos que permiten visualizar y comprender de manera más integral el comportamiento del cambio y establecer escenarios confiables que responda preguntas complejas sobre el tema a diferentes escalas de trabajo (Lu *et al.,* 2004).

Lambin *et al.,* (2006) señalan que dentro del Land-Use/Cover Change (LUCC) project (IGBP and IHDP) se plantean tres grandes estrategias de trabajo: i) dinámica de uso de la tierra, cuyo objetivo es analizar el procesos de cambio en diferentes contextos geográficos mediante meta análisis y proporcionar una perspectiva general sobre el cambio en meso y macroescalas; ii) cambio en la cobertura de la tierra, que se centra en identificar regiones o puntos calientes críticos de cambio y aplicar modelos basados en observaciones directas de variables explicativas; y iii) desarrollo de modelos globales y regionales, generalmente modelos espacialmente explícitos que ofrecen la posibilidad de observar patrones de cambio del uso del suelo ante escenarios de desarrollo.

Existe una diversidad de enfoques para analizar procesos LULCC relacionados con una amplia gama de preguntas de investigación; estos enfoques varían en escala, extensión, agentes, complejidad espacial y temporal y se pueden sintetizar en modelos estocásticos basados en matrices de transición y cadenas de Markov, modelos de optimización que incluyen modelos económicos (Kaimowitz & Angelsen, 1998), modelos de simulación (autómatas celulares), modelos basados en agente y modelos empíricos.

Verburg *et al.,* (2006), sintetizan los modelos en seis pares de categorías: i) espaciales vs. no espaciales, donde los modelos espaciales son capaces de explorar la variación espacial en el cambio de uso del suelo en función del entorno social y biofísico (ej. CLUE, GEOMOD y LMC) y los modelos no-espaciales se centran en conocer la tasa y magnitud del cambio de uso del suelo; ii) dinámicos vs. estáticos, los cuales se basan en las características temporales del cambio y su dinámica en función de una serie de hipótesis (ej. modelos de regresión) que se pueden usar para proyecciones futuras; iii) descriptivos vs. prescriptivos, los primeros simulan el funcionamiento del sistema de uso de la tierra ante patrones de uso, en contraste los prescriptivos optimizan el uso del suelo de acuerdo a unos objetivos; iv) deductivos vs. inductivos, los primeros basados en correlaciones estadísticas entre los cambios de la tierra y un conjunto de variables explicativas y los segundos donde los tomadores de decisiones especifican un conjunto de reglas de decisión cuyas interacciones se basan en las observaciones; v) basados en agentes vs. basados en pixeles, los cuales dependen de la unidad de análisis de cambio (polígono que representa una categoría de uso o una unidad de análisis para la toma de decisiones); y por último vi) modelos mundiales o regionales que varían de acuerdo a la extensión de los estudios.

Los enfoques espacialmente explícitos son los más usados en LUCC y fueron desarrollados originalmente para deforestación (Kaimowitz y Angelsen ,1998; Lambin, 1997); generalmente se basan en autómatas celulares o cadenas de Markov que simulan el cambio de uso del suelo en función de vecindades y un conjunto de relaciones y reglas de transición. Sin embargo no hay un enfoque único que explique el cambio en el uso del suelo; la elección del modelo depende del objetivo del trabajo o la toma de decisiones planteada y en muchos casos puede ser apropiado utilizar más de un modelo (Verburg *et al.,* 2006).

Por último cabe resaltar la importancia de los sistemas de información geográfica (SIG) y el desarrollo de algoritmos que permiten aplicar métodos de modelización de LUCC. Ejemplos de estos desarrollos son LCM (Land Change Modeler) integrado a Idrisi que analiza el cambio pasado de la tierra, modeliza el potencial de cambio futuro y predice la evolución de ese cambio frente a la biodiversidad o la planificación de la tierra; CLUE, modelo multiescala basado en la conectividad, organización jerárquica, estabilidad y capacidad de recuperación del sistema; y DINAMICA, que ofrece la posibilidad de dividir el área de estudio en sub-regiones, caracterizadas por diferentes dinámicas medioambientales y aplicar un enfoque específico para cada una de ellas (Paegelow & Camacho, 2008).

ESTRATEGIAS PARA MINIMIZAR EL IMPACTO DE LUCC EN LA CONSERVACIÓN

El manejo adecuado de los recursos es un desafío central de los responsables de formular políticas en diferentes esferas de la sociedad. De una parte se debe garantizar un suministro creciente de alimentos y otros servicios a las poblaciones humanas, y por otro lado, se deben plantear las posibles consecuencias de la degradación ambiental y sus implicaciones ante el cambio climático, la pérdida de biodiversidad y la contaminación. Por ello, los procesos de cambio del uso del suelo requieren soluciones locales y regionales y la cooperación de los responsables de la política mundial y otras partes interesadas en la gestión de la tierra a escala local, regional y mundial.

Algunas políticas, como las la creación de áreas protegidas, afectan directamente el uso del suelo y son fundamentales para las estrategias de conservación, ya que están diseñadas para salvaguardar los hábitats y las especies (DeFries *et al.,* 2005; Jope *et al.,* 2008). Sin embargo, la evaluación de la eficacia de estas figuras de protección es difícil, debido a la escasa disponibilidad de datos sobre las condiciones ecológicas y sociales y su cambio con el tiempo (Naughton-Treves *et* *al.,* 2005). Recientemente se han desarrollado otras estrategias de conservación como las reservas indígenas, y muchos creen que las comunidades indígenas son actores necesarios para la conservación a largo plazo de los bosques tropicales (Schwartzman y Zimmerman, 2005; Nepstad *et al.,* 2006), ya que sus prácticas tradicionales de manejo puede contribuir a mantener los valores naturales y culturales de una región (Román-Cuesta & Martínez-Vilalta, 2006; Nepstad *et al.,* 2006; Oliveira *et al.,* 2007).

El cambio en las causas de la deforestación desde el año 1985 ha creado nuevas oportunidades para la conservación de los bosques tropicales y dos estrategias de conservación parecen las más plausibles: la conservación de tierras altas mediante reservas (Andes) y la implementación de acuerdos de gestión de tierras bajas (Amazonia) (Rudel *et al.,* 2009). En las tierras altas, los bosques secundarios se han vuelto más comunes (Asner *et al.,* 2009), generalmente debido al abandono de tierras agrícolas. Su manejo y permanencia podrían tener implicaciones importantes para la conservación de la biodiversidad en estas áreas consideradas puntos calientes mediante el diseño de una red de reservas. En las tierras bajas, el aumento de la industrialización y los fondos de conservación de grupos conservacionistas internacionales, ONGs y un público nuevo preocupado por el impacto de la deforestación en el calentamiento global, hace posible una negociación entre las partes (Butler & Laurance 2008), poniendo de manifiesto un potencial de crecimiento para la certificación ambiental a fin de reducir los impactos de las empresas en los bosques tropicales (Rudel *et al.,* 2009).

A escala mundial, los esfuerzos para limitar las contribuciones de gases de efecto invernadero producto del cambio de uso del suelo pueden favorecer el manejo de bosques secundarios, el manejo de agroecosistemas y la reforestación. Las estrategias de Reducción de Emisiones por Deforestación y Degradación (REDD) (Butler & Laurance, 2008) pueden ser importante para los pequeños agricultores ya que proporcionan ingresos alternativos y una opción de mantener grandes áreas de bosque (Michalski *et al.,* 2010). A escala regional, la expansión de la agricultura debe estar limitada por un aumento en la productividad de las áreas que han sido previamente deforestadas, implementado directrices para frenar las amenazas de incendio debido al manejo del paisaje y las metodologías de zonificación ecológica-económica pueden ser estratégicas para mantener la conectividad de hábitat (Peres *et al.,* 2010).

Reid *et al.* (2006) plantean que es fundamental que los responsables de formular políticas cuenten con información acerca de las causas y consecuencias del cambio de uso del suelo, para crear instrumentos legales más eficaces y comprender los impactos de diferentes políticas sectoriales, económicas, energéticas, etc. ante LUCC. Algunos de los mensajes clave que proponen son: i) ciertos tipos de uso de la tierra son más sostenibles que otros; ii) el cambio del uso del suelo está dado por una combinación de factores; iii) las causas subyacentes de cambio generalmente de tipo global producen cambios locales en el uso de la tierra; iv) las políticas deben centrarse en los "puntos calientes" de cambio y degradación de tierras; v) algunas políticas benefician ciertos usos de la tierra mientras que otras no; vi) existen nuevos esfuerzos para evaluar el uso de la tierra y la reducción de la pobreza; y vii) debe existir un entendimiento de los actores clave y locales para el diseño de intervenciones de políticas exitosas.

COLOMBIA EN EL CONTEXTO DE LUCC Y DEFORESTACIÓN

Colombia ubicado en la zona noroccidental de América del Sur entre 12°26´46 N, 4°13´30 S, 66°50´54 E y 79°02´33, es reconocida como un país megadiverso que alberga el 10% de la biodiversidad del planeta. El país con una extensión de 1.14 millones de km^2 está conformado por cinco regiones naturales: Caribe, Andes, Amazonia, Orinoquia y Pacífico y aproximadamente un 52% del territorio está cubierto por ecosistemas naturales (bosques, páramos y sabanas). Históricamente en las regiones Andes y Caribe se ha desarrollado una intensa actividad antrópica desde épocas prehispánicas, siendo los bosques montanos y los bosques secos los ecosistemas más afectados por el cambio de uso del suelo desde el año 1500. Los impulsores directos de cambio estuvieron relacionados con la densidad poblacional y el establecimiento de actividades productivas intensas (café y ganadería) (Etter *et al.,* 2008).

A partir de 1600 hasta 1800, la población experimentó un aumento considerable, y la ganadería se expandió rápidamente en el Caribe, los Andes y la Orinoquia y la tenencia de la tierra en los Andes se caracterizó por la concentración de la propiedad. A partir de 1850 hubo un fuerte aumento en la producción agrícola estimulada por la demanda internacional de productos como el café y el tabaco, y un aumento en la producción ganadera debido a la introducción de pastos africanos. Hasta 1920 la región andina se caracterizó por una reocupación de las laderas, impulsada por factores como el crecimiento demográfico, las grandes inversiones en de la infraestructura ferroviaria y las exportaciones y a inicios del siglo XX (1920-

1970), se presento un crecimiento exponencial de la población, cambios tecnológicos en el sector agrícola (mecanización, uso de productos agroquímicos) y la migración rural-urbana, así como la dependencia en el sector cafetero. Actualmente, hay un continuo crecimiento poblacional, una creciente industrialización en torno a los grandes centros económicos ubicados en la región Andina (Bogotá, Medellín y Cali) y un aumento de la migración a las tierras bajas generalmente por conflictos armados (Etter *et al.,* 2008).

En los últimos 10 años ha habido un interés creciente en explicar los procesos de cambio de uso de la tierra; los primeros estudios generalmente se enfocaron a las zonas bajas, encontrando tasas de deforestación y su vínculo con algunas variables del paisaje y contextos socio-económicos (modelos no espaciales) (Viña & Cavelier, 1999; Armenteras *et al.,* 2006). Otros estudios han estimado probabilidades de deforestación en regiones bajas y vinculan algunas variables biofísicas y socio-económicas con este proceso (Etter *et al.,* 2005; Etter *et al.,* 2006a). A escala nacional (1:1.500000), Etter *et al.* (2006b) estudiaron los patrones agrícolas y de deforestación, mientras que a una escala más detallada (1:25000) Orrego (2009) utilizó modelos econométricos para examinar el uso del suelo en Antioquia (zonas altas).

A pesar del reconocimiento de la importancia de las actividades humanas como el principal motor y la modificación de la fuerza del LUCC (Veldekamp, 2009), en Colombia la comprensión de muchos de los procesos clave y las consecuencias para las especies y los ecosistemas siguen siendo insuficientes. Los estudios de LUCC son pocos y se han centrado en supervisar la deforestación y algunas causas de los cambio locales de usos de la tierra. Pese a ello hay grandes incertidumbres sobre la dinámica de cambio de uso en el país, que podrían incluir el estudio de diversas transiciones (intensificación agrícola, abandono, etc), la caracterización de patrones del paisaje o la efectividad de algunas estrategias de conservación frente a procesos de cambio.

OBJETIVOS Y ESTRUCTURACIÓN DE LA TESIS

El cambio de la cobertura y uso del suelo en los trópicos es un tema que ha cobrado importancia internacional en las últimas décadas, debido a que esta región contiene una alta biodiversidad y presta servicios de soporte y regulación tales como el clima y el agua. Mejorar la comprensión de estos procesos LUCC es un paso importante en el desarrollo de estrategias de planificación y conservación de la región. La mayoría de estudios en Colombia se han centrado en explicar los procesos de deforestación en bosques de tierras bajas (Amazonía) como una de las principales transiciones de LUCC. El objetivo de la presente tesis es mejorar la comprensión de los patrones, procesos y factores asociados al cambio del uso del suelo y la deforestación en las zonas tropicales, tomando como referencia dos regiones de Colombia: Andes y Guyana.

(1) La región de los Andes tropicales ocupa una superficie aproximada de 1.543.000 km^2, y contiene más de 100 tipos de ecosistemas, 45,000 plantas vasculares (20,000 endémicas) y 3400 especies de vertebrados. Por ello es considerada como una de las ecorregiones terrestres prioritarias para la conservación de la biodiversidad a nivel mundial (Myers *et al.,* 2000). Los Andes están sujetos a una alta presión antrópica que acelera los procesos de cambio del uso de la tierra, la erosión del suelo y la destrucción del hábitat (Achard *et al.,* 2002; Grau & Aide, 2008). Los Andes colombianos, cubren más de 9 millones de hectáreas y cerca del 35% está cubierto por ecosistemas naturales. Es un buen caso de estudio dentro del sistema montañoso de América del Sur debido a su ubicación geográfica y a sus procesos de conversión del suelo. La región está conectada con los bosques del Choco biogeográfico, el Caribe, el Orinoco y la cuenca del Amazonas.

(2) La región del escudo de Guyana ocupa aproximada 2,5 millones de km^2 y se caracteriza por la baja densidad poblacional y los altos niveles de conservación de ecosistemas naturales (entre el 80 y 90%). Presenta una elevada complejidad florística y ecológica, estimándose más de 20.000 especies de plantas vasculares, 35% de las cuales se consideran endémicas. En Colombia, el Escudo Guayanés se ubica entre las cuencas del Amazonas y del Orinoco, ocupando cerca de 13 millones de hectáreas, donde los procesos de deforestación son bajos y donde la mayor parte del área (51%) se encuentra bajo alguna categoría de manejo (Parques o Reservas Nacionales Naturales o Resguardos indígenas). Es un buen caso de estudio para las tierras bajas de Colombia.

La tesis está compuesta por cuatro capítulos en formato de artículo científico. Los dos primeros estudian la dinámica de LUCC en la región Andina y los factores de cambio; el capítulo 3 y 4 se orientan a evaluar los patrones de cambio y la efectividad de las áreas protegidas frente a los procesos de deforestación en la región Guyanesa.

Capítulo 1. En él se evalúa la importancia relativa de las variables humanas y naturales en la deforestación de los Andes de Colombia entre 1985 y 2005, utilizando sensores remotos, sistemas de información geográfica (SIG) y modelos lineales generalizados (GLM). Los resultados de este capítulo proporcionan elementos para comprender las diferentes dinámicas que ocurren en los bosques de tierras bajas en comparación con los bosques montanos.

Capítulo 2. En este primer apartado de la tesis se cuantifica el cambio de cobertura y uso del suelo LUCC ocurrido entre 1985 y 2005 en los Andes colombianos, mediante el empleo de imágenes de satélite y mapas de cobertura y utilizando el programa Land Change Modeler. Se analizan cuatro submodelos de cambio, asociándolos a variables demográficas, socioeconómicas, de uso del suelo, abióticas y algunos atractores. A partir de este estudio se plantean y discuten diferentes escenarios de cambio.

Capítulo 3. Se analizan cuatro modelos diferentes de ocupación humana (indígenas, colonos, transición y asentamientos establecidos) en el Escudo Guayanés colombiano en tres fechas diferentes: 1985, 1992 y 2002. El estudio compara: las tasas de deforestación, la cantidad de bosques clasificados de acuerdo a un patrón de fragmentación y varias métricas fragmentación mediante análisis ANOVA de medidas repetidas. Finalmente, en el capítulo se evalúan las perspectivas de deforestación mediante la aplicación de un modelo de simulación espacialmente explícito.

Capítulo 4. En este capítulo se analiza la eficacia de algunas estrategias de conservación como las áreas protegidas y reservas indígenas ante el proceso de deforestación en el Escudo Guyanés de Colombia. Se evalúa el éxito en detener la deforestación y la expansión de la frontera agrícola mediante la comparación de la deforestación producida dentro y fuera de estas áreas entre 1985-2002. También se analiza el papel de tres factores, las carreteras, los cultivos ilícitos y la superficie del área protegida, en las tasas de deforestación.

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CHAPTER 1

UNDERSTANDING DEFORESTATION IN MONTANE AND LOWLAND FORESTS OF THE COLOMBIAN ANDES

Armenteras, D., Rodríguez, N., Retana, J. and Morales, M. Understanding deforestation in montane and lowland forest of the Colombian Andes. (2011). *Regional Environmental Change* 11, 693-705.

1. UNDERSTANDING DEFORESTATION IN MONTANE AND LOWLAND FORESTS OF THE COLOMBIAN ANDES

ABSTRACT

Colombian Andean forests cover nine million ha. These forests provide an informative case study of mountain deforestation in South America. They are surrounded by tropical lowland forests, and they host most of the country's human population. This study evaluates the relative importance of human and natural variables in deforestation of the Colombian Andes between 1985 and 2005 using remote sensing methods, Geographic Information System (GIS) technology and General Linear Models (GLM). The following factors affected the annual deforestation in the region positively: forced population migration, unsatisfied basic needs, economic activity, crops, pastures, illicit crops, protected areas and slope. Factors having a negative effect were tenure of small land parcels, road density, water scarcity and mean temperature. The results of this study also provide insight into the differences between the dynamics of lowland forests and those of montane forests. Montane forests had a lower annual rate of deforestation than did forests in the lowlands. Socioeconomic, demographic and biophysical factors explain overall deforestation rates for the region. However, when altitude variation is taken into account, intraregional differences in the Andes become evident. Deforestation processes differ between those areas adjacent to the high Andean valleys where most of the country´s population concentrates and those areas in the tropical lowlands north, west and east of the Andean chain. Differences between lowland and montane forest dynamics are due partly to the accessibility of forests and differences in wealth and economic activities. In montane forests, deforestation is positively influenced by economic activity, the presence of protected areas and higher slopes. Deforestation in montane forests is negatively affected by tenure of small land parcels, road density, water scarcity and mean temperature. Lowland deforestation rates are more closely related to rural population, pasture percentage, crops, protected areas and temperature. Our results suggest that montane forests appear to be in a more advanced stage of colonization and economic development, whereas lowland forests are closer to the colonization frontier and to rapidly-growing colonist populations. This study reinforces the idea that although the most common tropical drivers of deforestation are found in the Andes, these drivers operate differently when intraregional differences are considered.

Keywords: deforestation, Andes, GLM, montane forests, lowland forests, driving factors, Colombia

1.1. INTRODUCTION

Tropical forests are widely acknowledged as key systems for many aspects of life on earth, including not only environmental and ecological factors but also social, cultural and economical components of human life (Wright, 2005; Foley *et al.,* 2007; Naidoo *et al.,* 2008). However, recent estimates highlight the high percentage of CO_2 emissions that tropical deforestation contributes globally (Fearnside, 2000; Achard *et al.,* 2002; Santilli *et al.,* 2004). Tropical deforestation is important to the global carbon cycle and it contributes to global change. Increasing awareness about the progress and consequences of tropical deforestation in recent decades has driven many researchers to understand what factors direct the course of this process. The majority of regional models of tropical deforestation that have been developed in recent years include a combination of economic, demographic, institutional, natural and policy factors that vary according to the spatial and temporal scale of the area studied (Brown & Pierce, 1994; Geist & Lambin, 2002; Rudel, 2006; Kindermann *et al.,* 2008). Recently, some authors have suggested that there are great temporal changes in the forces that drive tropical deforestation from old governments' rural settlement schemes to more enterprise-driven processes and current large-scale agricultural producers, such as large-scale soybean farming in Brazil (Rudel, 2007; Vera-Diaz *et al.,* 2008). The factors driving deforestation are often economically driven, and many of the current statistical models used are econometric models that use data at the municipal level (Dutra-Aguiar *et al.,* 2007). Other attempts to model tropical deforestation have used artificial neural networks linking deforestation to selected environmental and socio-economic spatial variables such as elevation, slope, type of soil, distance from forests to roads or to settlements or spatial fragmentation (Mas *et al.,* 2004). Some key studies during the last decade (Geist & Lambin, 2002; Rudel, 2007; Butler & Laurance, 2008) suggest that common deforestation patterns can still be found but a multiple factor approach should be evaluated and the variability of circumstances over time should also be considered when studying forest loss (Rudel, 2007).

For decades, tropical deforestation studies have been carried out with an emphasis on lowland tropical forests. For example, most deforestation studies in South America have been centered in the Amazonian basin (Camara *et al.,* 2005; Fearnside

2005; Kirby *et al.,* 2006; Foley *et al.,* 2007; Malhi *et al.,* 2008). However mountain areas represent an important percentage of South America. The tropical Andes hotspot (identified by Myers *et al.,* 2000) covers 1,258,000 km^2 and this area has rarely been considered in deforestation studies. Globally, mountain areas are considered an essential source of ecosystem services. For example, mountain areas influence the hydrological cycle, thus providing water to populations living in mountain areas as well as in lowland settlements (Gomez-Peralta *et al.,* 2008). Mountains are often considered major centers of biological diversity and cultural diversity (Fjeldsa *et al.,* 1999). Tropical mountains, such as the Andes in South America, are of particular interest given their high vulnerability to global change (Bush *et al.,* 2004), and Andean forests are particularly susceptible and highly vulnerable to climate change because of their location on steep slopes and because of their altitudinal and climatic gradients (Kalmalkar *et al.,* 2008). I addition to climate change, tropical mountains are subject to high pressure from other natural and anthropogenic drivers of change that range from land use and land cover change, soil erosion, landslides and habitat destruction, amongst others (Achard *et al.,* 2002; Bush *et al.,* 2004; Grau & Aide, 2008).

In South America, the Andes are the home to almost 40 million inhabitants and thereby have an important economic and ecological, role. Historically, the underlying causes of forest loss in the Andes have been large-scale cattle ranching, agriculture and clearance for government planned settlement schemes (Etter *et al.,* 2006; Grau & Aide, 2008). More recently, forest has been replaced with illicit crops, especially in Colombia, Peru and Bolivia (Bradley & Millington, 2008). Population pressure is also considered one of the most important pressures on forest change in the Andes. Population growth in mountainous areas exceeds the national average and tends to concentrate people along transportation routes. Recent studies relate deforestation to environmental, population and economic factors in the highland forests of Ecuador (Keese *et al.,* 2007), Bolivia (Killeen & Solórzano, 2008), Peru (Kintz *et al.,* 2006) and Colombia (Etter *et al.,* 2006). In contrast to the most recent factors that have driven the disappearance of lowland forests (Rudel *et al.,* 2009), large enterprisedriven deforestation has been identified as a major driver of mountain forest deforestation in only a few cases, such as with dry tropical forests in Bolivia (Killeen & Solorzano, 2008). Lowland tropical forests are historically different from mountain forests in terms of land use, demography and economic activities, both in their intensity and change rates. Large-scale (e.g., cattle ranching) and small-scale farming were historically the most significant drivers of deforestation in the Amazon. These farming activities resulted from favourable incentives received by cattle ranchers in the 1960s–1980s.

More recently, the establishment of soy farming has become a land-demanding economic activity (Kirby *et al.,* 2006; Rudel *et al.,* 2009).

Colombian Andean forests cover over 9 million ha and are a good case study within the South American mountain system due to their particular geographical location. Colombian Andean forests are connected to the Caribbean Pacific, Orinoco and Amazon basin areas of tropical lowland forests. This paper analyses the effect of both human-related and environmental forces driving deforestation in the Colombian Andes. As topographical differences have been largely ignored in attempts to model deforestation processes we also look into topographical differences to model deforestation processes in this region, focusing on how much the deforestation drivers (both natural and human activities) vary when taking into consideration altitude variations. Our aim was to detect whether there are intraregional differences in the Andes and how deforestation processes differ between those areas adjacent to the high Andean valleys where most of the country´s population concentrates and those areas in the tropical lowlands, north, west and east of the Andean chain.

1.2. MATERIALS AND METHODS

STUDY AREA

The Andes mountain range stretches from Chile to Venezuela for more than 8,000 km. It is a massive mountain range that influences many physical and biotic processes in South America (Ramos, 1999; Braun *et al.,* 2002). With an extent of nearly 8.1 million km^2 and peaks above 4000 m, this cordillera (and specifically its tropical sector) has been repeatedly considered a global conservation priority because of its biological diversity, endemism and vulnerability (Mittermeier *et al.,* 1999; Myers *et al.,* 2000; Olson & Dinerstein, 2002).

In Colombia, the Andes split into three cordilleras (Western, Central and Eastern) that surround the Magdalena-Cauca valley, which is one of the main watersheds of the country (Figure 1.1). Even though the area of the Colombian Andes (287,720 km^2; 400 m and above) only represents 25% of the total area of the country, 70% of Colombia’s population is within the mountain range (Armenteras & Rodríguez, 2007). The human occupation of the Colombian Andes dates back to pre-Hispanic times and has been increasing since the 1950s. This increase in montane areas is due to urbanization processes and in lowland areas is associated wiyh migratory phenomenon resulting from of the colonization front, leading to a substantial change in natural landscape (Armenteras & Rodríguez, 2007). Crops like coffee and potato, cattle pastures, illicit cultivation and urban development (Cavelier & Etter, 1995; Armenteras *et al.,* 2005) have affected the wide diversity of Colombia's Andean ecosystems. By 2000, only 39.5% of the natural cover remained (Rodriguez *et al.,* 2006). Due to its exceptional diversity and vulnerability, a considerable number of protected areas have been established in the Colombian Andes. However, only 8.4% of the area is nationally protected (Morales, 2007). Thus, the effective protection of mountain forests is not guaranteed (Armenteras *et al.,* 2003).

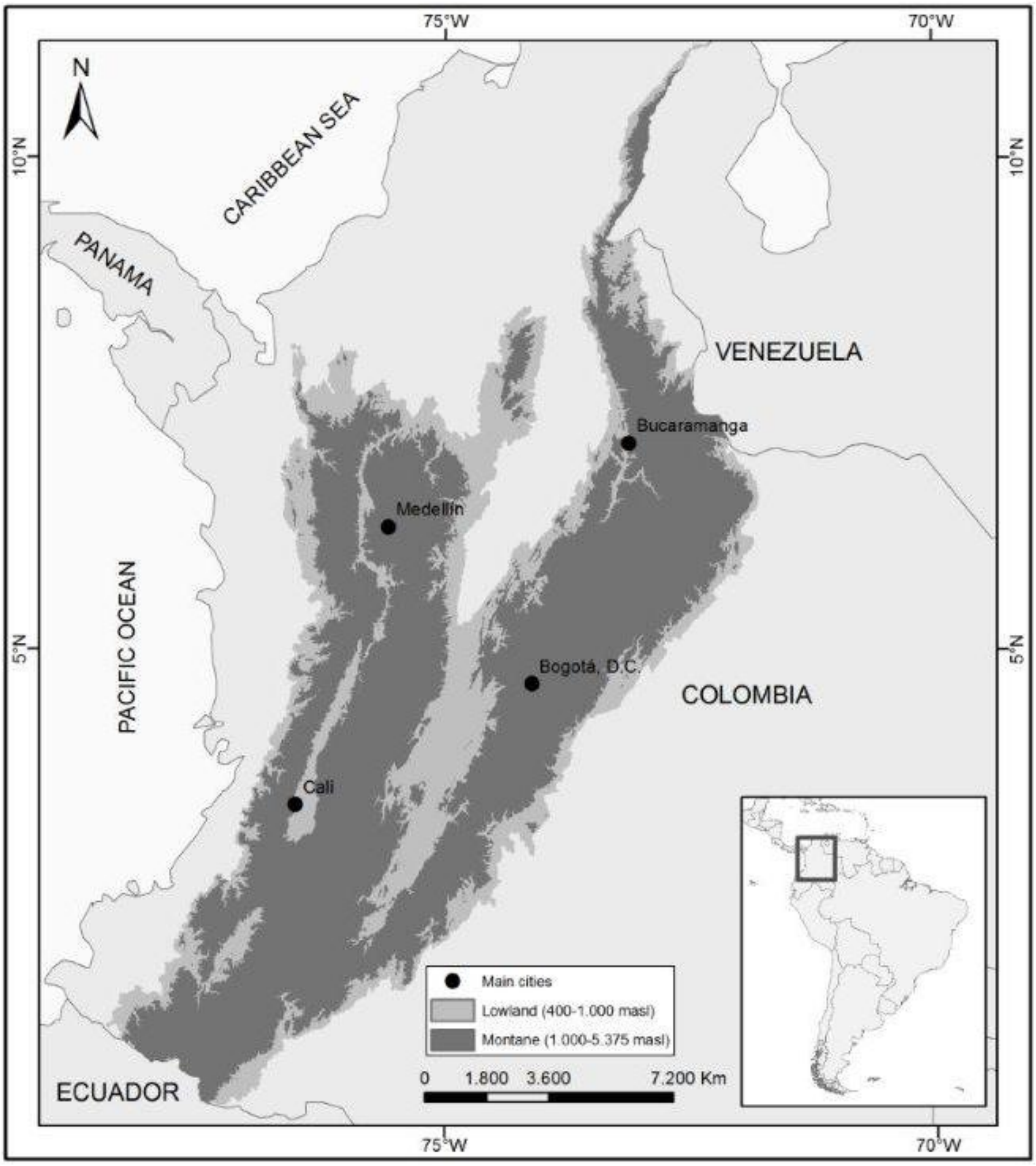

Figure 1.1 Study area.

Andean forest zonation is mainly defined by altitude because of its influence on temperature and orographic rainfall. A number of different classification systems have been used in South America (Holdridge, Grubb, UNESCO and IUCN), with each country adopting its own variation of one of these systems. Generally, low elevation rainforests (<900–1000 m) are followed by montane forests (1000–3500 m). In a Colombian montane forest ecoregion study focused on the eastern flank of the Andes, Armenteras *et al.,* (2003) adopted a zonification that differentiated sub-Andean montane forests (1000–2000 m) and Andean montane forests (2000–3500 m). For the purpose of this study, we established a 1000 m elevation limit (Figure 1.1) and considered all forests below 1000 m as lowland forests, including those that are near the Andean piedmont and lowland tropical areas such as the Amazonia, Orinoco and Pacific regions, and all forests above 1000 m as montane forests.

DEFORESTATION MAPS

Remote sensing data from over 70 Landsat multispectral satellite images using Multispectral Scanning (MSS), Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM) dated from 1985 and 2005 from a previous study were used (Rodríguez *et al.,* 2006). The Landsat data was geometrically corrected and georeferenced to the Transverse Mercator projection, Datum Bogotá Observatorium, International Ellipsoid of 1909, Latitude 4° 35” 56.57” N; Longitude 74° 4’ 51.3 W. This projection was used to integrate all variables into GIS. The best images for the construction of the 1985 and 2005 forest maps were used and interpreted at the scale of 1:250,000. Given the high cloud and shadow cover of some areas of the Andes, more than one scene was combined to generate the land cover map for both years with a total cloud and shadow cover below 7%. Furthermore, due to technical problems (banding) of Landsat after 2003, the 2005 land cover map was completed using SPOT and Aster imagery and deforestation spatial data provided by SIMCI (UNODC, 2006). A mixed digital supervised classification with on-screen visual interpretation was carried out using ERDAS Imagine V8.7 software (Leica Geosystems 2005). Image interpretation was aided by detailed information from vegetation and soil cover maps that exist for some departments (IGAC-ICA, 1985; IGAC-Corpoica 2002). Images were classified into the following major land cover classes according to their imagery spectral response as follows: forests (including dry forests), secondary vegetation (second growth vegetation of early and intermediate stages), agriculture, pastures and other (including eroded, forest plantations, urban areas and roads). To analyse the altitudinal differences in deforestation, two different classes of forest were created using the altitudinal line of 1000 m, thus differentiating lowland and montane forests.

A sequence of filters and data depuration was carried out. First, statistic filters were applied to the original cover to eliminate pixels that were misclassified. Next, a boundary clean function was performed to soften borders between different classified areas. A minimum mapping unit of 25 ha was used. Images were classified independently and both post-classification field verification and statistical validation were performed. For the 2005 map, we used 372 verification points obtained from field data stratified according to the size of the polygons (Medinger, 2000) and available detailed land cover maps (IGAC, 2002) for some regions and aerial photographs to obtain an overall global accuracy and Kappa coefficient of 90.4% (Rodriguez *et al.,* 2006). For the 1985 map, we used secondary information from regional and local land use maps (IGAC-ICA 1985, IGAC-Corpoica, 2002) for those 372 points, achieving an accuracy of 83.7%.

Forest maps for both periods were incorporated into GIS using ArcGIS. An overlaying analysis was performed to assess deforestation areas observed between the two periods analysed and locate sites where deforestation occurred. The analysis was focused on 627 municipalities in the Colombian Andes (only those that have more of 50% of their rural territory in the Andes region). Of these municipalities, 139 of them had lowland forest and 623 had montane forest. Deforestation rates for all forests, and then for both montane forests and lowland forests, were assessed based on the forest maps. Following Fearnside (1993), we computed deforestation rate (R, in %) within the Andes region as follows:

$$R = ((A_{1985}-A_{2005})/(A_{1985}*t))*100$$

where A_{1985} and A_{2005} are forest areas in 1985 and 2005, respectively, and t is the time interval in years (in this study, the time interval was 20 years). We also computed R for each municipality. We considered montane and lowland forests separately.

For the statistical analysis of the effect of the different variables considered on deforestation at the municipal level, we weighted the size of the forests in a municipality (otherwise municipalities with small forests would count as much as municipalities with large forests). We applied a factor derived from the contribution of the forest area within each municipality (A_{1985m}) with respect to the total forest in the

Andes region (A_{1985}) in 1985. From these considerations, we calculated each municipality's rate of deforestation contribution (R_m) to R as follows:

$$R_m = ((A_{1985m}-A_{2005m})/(A_{1985}*t))*100$$
with $R = \sum R_m$.

DATASETS USED FOR INDEPENDENT VARIABLES

The analysis concentrated on the 627 forested municipalities of the Andes during the 1985-2005 period. The selected possible explanatory variables for deforestation at the regional level were demographic, socioeconomic, land use and physical environmental variables (both abiotic and biotic). A GIS database of independent variables that could be considered as elements influencing deforestation in the region *a priori* was integrated using the municipality as the basic spatial analysis unit. Originally, there were 75 variables. We reduced this to 20 variables (Table 1.1) to avoid using highly correlated variables or variables with missing data.

Demographic and socio-economic data were obtained from the national population census at the municipal level from the National Administrative Department of Statistics. This dataset included data on literacy rates, unsatisfied basic needs (a commonly used composite indicator combining census level household measures such as access to adequate housing conditions, water, electricity and sanitation; Feres and Mancero, 2001), quality of life, number of inhabitants (rural and urban) and forced migration. Most of the demographic and socioeconomic data were obtained from the 1985, 1993 and 2005 population census (Departamento Administrativo Nacional de Estadística-DANE, 1985, 1993, 2005). Digital maps of national protected areas, indigenous reserves, municipalities, road networks and human settlements were obtained from the Agustin Codazzi National Institute of Geography (IGAC, 2005) at a scale of 1:500.000. IGAC also provided us with the digital elevation model based on the Shuttle Radar Topography Mission (SRTM, 90 m resolution) from which a slope map (in degrees) was derived. Climatic variables, such as mean annual temperature and annual precipitation, were derived from a climatic database of meteorological stations, interpolated and then summarised for the territory of each municipality (IDEAM, 2006). We used spatial analysis techniques, including neighbourhood and distance calculations, map algebra, and reclassification, to analyse physical environmental variables in GIS.

Table 1.1 Summary of the variables considered in the deforestation analysis and dataset sources.

Type	Short name	Units	Description	Source
Demographic	*Urban population*	Number of inhabitants	Absolute change of urban population between 1985-2005	National Administrative Department of Statistics (DANE) 1985,1993,2005
	Rural population	Number of inhabitants	Absolute change of rural population between 1985-2005	National Administrative Department of Statistics (DANE) 1985,1993,2005
	Forced population migration	Number of people	Number of people forced to leave their lands by illegal armed groups or displaced population	Consultoría para los Derechos humanos y el desplazamiento- Codhes 2005
Socio economic	*Small land parcels tenure*	%	Percentage of small land parcels tenure per municipality in 1995	Ministerio de Agricultura y Desarrollo Rural. Censo de minifundio en Colombia. 1995
	Quality of life	Unitless	Quality of life (ICV, Indice de Calidad de Vida) is a composite index with values between 0 and 100 that represent the minimum and maximum possible level of population quality of life respectively. Includes information on education, family size, household building quality material, water availability, garbage collection, household density and income.	Colombian National Planning Department. 2003.
	Literacy rates	% of population	Literacy rates per municipality.	National Administrative Department of Statistics (DANE) 1985,1993, 2005
	Economic activity	Million Colombian pesos	Taxes revenues per municipality, equivalent to tax income in million Colombian pesos in 2005.	National Planning Department (Departamento Nacional de Planeación-DNP, 2008) and the Unified Information System for (Sistema Único de Información de Servicios Publicos-SUI, 2008).
	Unsatisfied basic needs	*%*	% of population with unsatisfied basic needs in 2005. In Latin America, most countries consider as basic needs minimum household conditions, access to sanitary services, access to primary education and minimum economic capacity of the household.	National Administrative Department of Statistics (DANE) 2005
	Energy consumption	Kw/h	Municipality energy consumption in 2005	National Planning Department (Departamento Nacional de Planeación-DNP, 2008) and the Unified Information System for (Sistema Único de Información de Servicios Publicos-SUI, 2008).

Type	Short name	Units	Description	Source
Land Use	*Crops*	Ha	Total change of crop area (in ha) between 1985-2005 derived from the satellite image classification	Calculated
	Pastures	Ha	Total change in ha of area under pastures	Calculated
	Illicit crops	Ha	Area under coca *(Erythroxylum coca)* crops	United Nations Office on Drugs and Crime (UNDOC, 2006), through the Colombian Integrated System for Illicit Crops Monitoring project or SIMCI (Sistema Integral de Monitoreo de Cultivos Illicitos)
	Coffee Area	Ha	Area under coffee in 2005	Colombian Coffee Federation, 2005
	Protected area	Ha	Area of each municipality under special management either under category of national protected area or indigenous reserve.	IGAC 2005 Calculated
Physical Environment	*Road density*	km/ha	Density of roads in km/ha was calculated also for each one of the municipalities.	IGAC 2005 Calculated
	Distance to nearest forest fragment	kilometers	Distance of the urban center of each municipality to the nearest forest fragment existing in 1985 (in km) for all 3 forest types (montane, lowland, and total Andean)	Calculated based on forest map 1985 and Urban Centers provided by IGAC (2005)
	Maximum slope	Degrees	Maximum Slope (in degrees) for each municipality was calculated representing their average values for each municipality.	Calculated (IGAC 2005).
	Water scarcity in dry years	%	Index of water scarcity in a dry year.	IDEAM, Instituto de Estudios Ambientales y Meteorológicos. 2000
	Temperature	~C	Annual mean temperature	Calculated from climatic database
	Precipitation	Mm	Annual precipitation	Calculated from climatic database

STATISTICAL ANALYSES

The comparison between annual deforestation rates per municipality of montane and lowland forests was carried out with a Student t test after log transformation of the data. A General Linear Model (GLM) was used to explore the relationships between deforestation and the different demographic (urban population, rural population, forced population migration), socioeconomic (small land parcels tenure, quality of life, literacy rates, economic activity, unsatisfied basic needs, energy consumption), land use (crops, pastures, illicit crops, coffee area, protected areas) and physical environment variables (road density, distance to nearest forest fragment, maximum slope, water scarcity in dry years, temperature, precipitation). We specified the three following different GLM models for deforestation: one for the total forest area (all forested area in the Andes without altitudinal differentiation), one for montane forests and one for lowland forests. All parameters were estimated by maximum likelihood, and given the high number of data in our analyses, significance was accepted at $p=0.01$. To normalise the data, several variables (deforestation, water scarcity in dry years, urban population, rural population, economic activity, energy consumption, illicit crops, protected area, and distance to nearest forest fragment) were log-transformed. Statistical analyses were carried out using STATISTICA 6.0.

1.3. RESULTS

Total forest in the whole study area decreased from 11,006,893 ha in 1985 to 9,528,961 ha in 2005 (0.67%), which represented a forest loss from 7,335,125 ha to 6,405,591 ha (0.63%) in montane forests and from 3,671,768 ha to 3,123,369 ha (0.75%) in lowland forests (Figure 1.2). In total, 616 out of 627 municipalities lost a variable proportion of their forests. Annual deforestation rates per municipality of montane and lowland forests were not significantly different (Figure 1.3; Student t test, $p>0.01$).

The best model of total deforestation ($R^2=0.55$, $p<0.001$, $N=627$) included the effects of four demographic and socioeconomic variables (forced population migration, small land parcels tenure, unsatisfied basic needs and economic activity), four land use variables (crops, pastures, illicit crops and protected areas) and four physical environment variables (road density, maximum slope, water scarcity in dry years and mean temperature). In regards to the demographic and socioeconomic variables

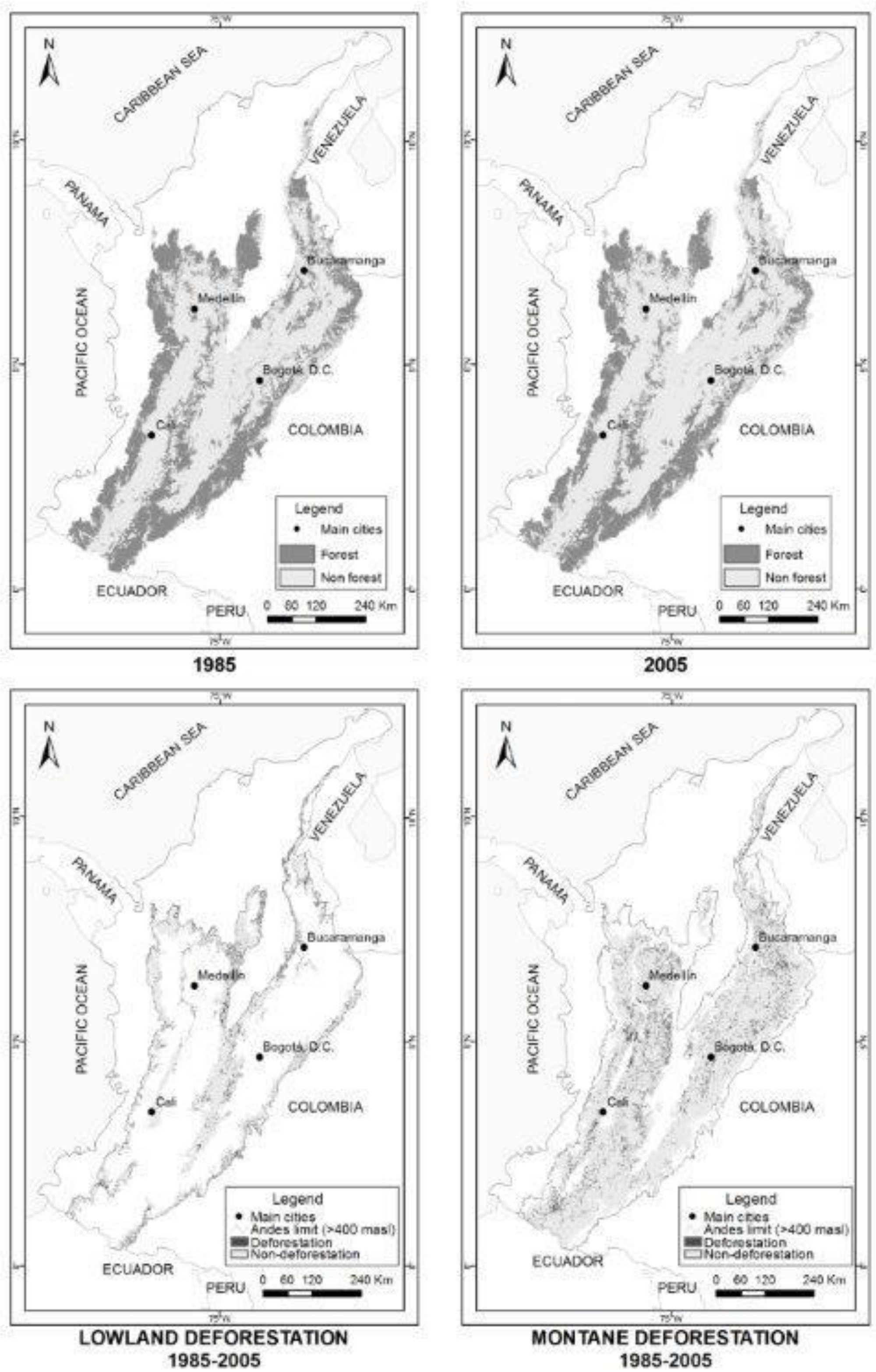

Figure 1.2 Lowland and montane forests in 1985 and 2005 and deforestation hotspots between these dates.

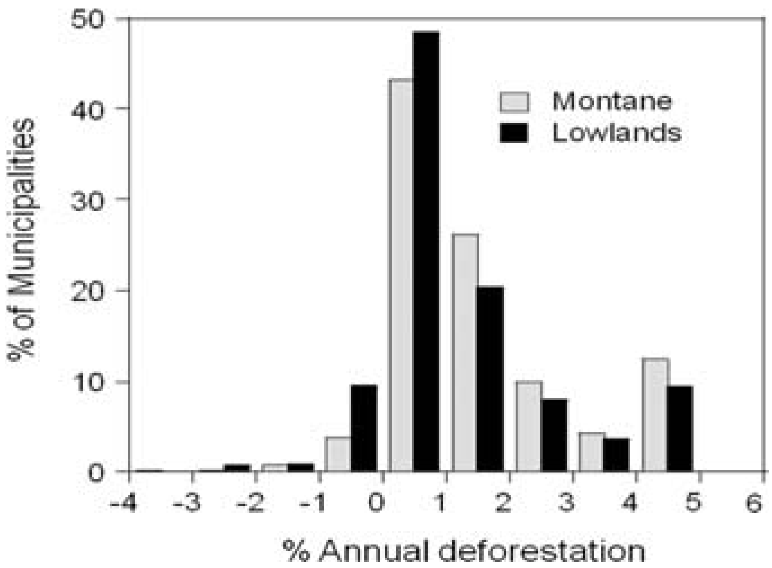

Figure 1.3 Percentage of municipalities in the Andes with different rates of deforestation in montane forests (N=623, grey) and lowland forests (N=139, black).

included in the model, unsatisfied basic needs and forced population migration had a significant positive effect on deforestation, indicating that forest loss was higher in municipalities with high poverty and migration; economic activity also positively influenced deforestation, while deforestation increased in municipalities with lower proportion of small land parcels tenure. The four land use variables included in the model affected positively deforestation rate, which increased with the increment of crops, pastures and illicit crops and the presence of protected areas in the municipality. In regards to physical environment variables, deforestation rate increased significantly with mean temperature and water scarcity but declined with road density and maximum slope (Table 1. 2a).

In the case of montane forests (Table 1.2b), the best model of deforestation (R^2=0.38, p<0.001, N=623) included the effects of two demographic and socioeconomic variables (small land parcels tenure and economic activity), one land use variable (protected areas) and four physical environment variables (road density, maximum slope, water scarcity in dry years and mean temperature). In all cases the effect of these variables on deforestation in highlands was similar to their effect on total deforestation (Table 1.2b).

The best model of deforestation in lowland forests (R^2=0.67, p<0.001, N=139) included the effects of one demographic variable (rural population), three land use variables (crops, pastures and protected areas) and one physical environment variable (mean temperature). Deforestation was positively related to the increment of all these five variables (Table 1.2c).

1.4. DISCUSSION

People have lived in the Andes of South America for centuries, and the pressure that humans have exerted upon the natural resources can possibly be traced back to pre-Columbian civilisations. However, the degree of impact has been different across different regions of South America. In particular, the Colombian Andes deforestation rate of 0.67% is slightly higher than average reported rates for South American forests (0.38%, Achard *et al.,* 2002; 0.6% WCMC, 2000). Overall, socioeconomically important factors such as economic activity, population, roads and the proximity to local markets have strongly affected deforestation processes across the tropics (Vance & Iovanna, 2006; Rudel & Roper, 1997; Etter *et al.,* 2005). These factors also influence deforestation in the Andes.

In general, the understanding of deforestation in the Andes region falls within two sets of theories of deforestation in the tropics, those that identify networks of entrepreneurs, companies, and small farmers as the chief agents of deforestation and those that focus on growing populations of peasants and shifting cultivators (Rudel & Roper, 1997). In wealthier Andean municipalities, economic activity and concentration of land tenure, rather than poverty, drives deforestation. Although the Andes are a highly transformed area of Colombia and over 60% of the range has already lost its natural coverage, the Andes are still in an economic or developmental stage of natural resource extraction (exploitation, settlement and deforestation). The Andes are an economically active area with higher tax revenue incomes than the rest of Colombia, largely because of the intensive use of the territory, including land use change from forest to pastures and other agriculturally productive activities. This activity is also linked to transportation development that has made the territory more accessible. This increased accessibility might initially have caused deforestation in flat areas, which are adequate for agricultural activities and which have subsequently been transformed in order to support productive activities. Moreover, land tenure plays an essential role in the Andes. Concentration of land tenure (i.e., fewer small land parcels) has led to higher deforestation. However, inaccessible areas, where most forests are concentrated, have lower road density, steeper slopes and a tendency to attract illegal cropping. Inaccessible areas have higher deforestation rates. Historically, because access to these areas has always been difficult, the areas in question have harbored

Table 1.2 General linear model for deforestation of (A) all forests, (B) montane forests, and (C) lowland forests of Andean municipalities as a function of different demographic (urban population, rural population, forced population migration), socioeconomic (small land parcel tenure, quality of life, literacy rates, economic activity, unsatisfied basic needs, energy consumption), land use (crops, pastures, illicit crops, coffee area, protected area) and physical environment variables (road density, distance to nearest forest fragment, maximum slope, water scarcity in dry years, temperature, precipitation). Significant values at p<0.05 are in bold. N=627, 623 and 139 municipalities, for the total, montane and lowland analyses, respectively.

	Total			**Montane**			**Lowland**		
Variable	**F**	**P**	**Beta**	**F**	**P**	**Beta**	**F**	**P**	**Beta**
Urban population	0.4	0.533	-0.026	0.6	0.439	-0.038	4.5	0.036	-0.141
Rural population	0.0	0.912	0.003	0.8	0.374	-0.034	**6.7**	**0.009**	**0.179**
Forced population migration	**19.3**	**<0.001**	**0.144**	3.8	0.050	0.080	0.7	0.402	0.056
Small land parcels tenure	**17.0**	**<0.001**	**-0.124**	**18.0**	**<0.001**	**-0.151**	0.0	0.845	0.011
Quality of life	1.6	0.211	-0.073	1.6	0.201	-0.088	0.4	0.528	0.065
Literacy rates	1.9	0.163	0.066	6.0	0.014	0.137	0.2	0.629	0.041
Economic activity	**30.7**	**<0.001**	**0.285**	**31.6**	**<0.001**	**0.341**	5.5	0.020	0.173
Unsatisfied basic needs	**8.8**	**0.003**	**0.138**	4.5	0.033	0.117	1.3	0.254	0.101
Energy consumption	1.3	0.246	0.041	0.5	0.480	0.030	0.2	0.498	0.044
Crops	**19.7**	**<0.001**	**0.134**	4.6	0.032	0.080	**13.5**	**<0.001**	**0.225**
Pastures	**25.2**	**<0.001**	**0.148**	3.4	0.064	0.065	**23.2**	**<0.001**	**0.308**
Illicit crops	**12.0**	**<0.001**	**0.127**	4.0	0.046	-0.086	6.5	0.011	0.200
Coffee area	1.6	0.196	0.037	2.3	0.125	0.051	4.8	0.030	0.153
Protected area	**34.4**	**<0.001**	**0.195**	**18.6.0**	**<0.001**	**0.169**	**9.8**	**0.002**	**0.228**
Road density	**13.6**	**<0.001**	**-0.130**	**6.8**	**0.009**	**-0.109**	4.2	0.041	-0.161
Distance to nearest forest fragment	0.6	0.448	-0.021	2.6	0.101	0.070	1.8	0.180	-0.090
Maximum slope	**33.2**	**<0.001**	**0.170**	**39.2**	**<0.001**	**0.218**	2.7	0.102	0.098
Water scarcity in dry years	**22.6**	**<0.001**	**-0.176**	**17.6**	**<0.001**	**-0.188**	3.2	0.073	-0.143
Mean temperatura	**10.0**	**0.002**	**-0.114**	**27.8**	**<0.001**	**-0.224**	**22.5**	**<0.001**	**0.373**
Annual precipitation	0.35	0.590	0.021	0.4	0.515	0.032	3.4	0.068	-0.130

violent illegal groups and have consequently experienced higher forced population displacement rates. Higher unsatisfied basic needs are reflected in higher forced migrations (involuntary displacement of the population due to illegal armed groups). Such dissatisfaction and its consequences might lead in turn to a decline in economic activity of some areas and to a corresponding increase in pressures in those areas into which populations are forced to migrate. In turn, these changes lead to increases in pastures and in cropland. Environmental aspects of the Andes also help to explain the high deforestation rates we found. Specifically, lower temperatures and less water scarcity were associated with higher rates of deforestation, especially in montane forests close to paramos and near urban centres. The protected areas were positively associated with deforestation might reflect the fact that many protected areas are located in remote and less-accessible districts. Historically, this is indeed the case for many highland parks established in the Andes (Armenteras *et al.,* 2003).

In addition to the general trend towards deforestation in the Andes of Colombia, local differences occur between lowland and montane forests within the region. These differences may be related to two of the traditional explanations of deforestation in the tropics (Rudel & Roper, 1997) and may support the suggested curvilinear relationship between economic development and deforestation. Rudel & Roper (1997) presented these two traditional explanations. First, deforestation was associated with the very poorest areas. These populations had no opportunities other than those resulting from land clearing. Second, deforestation was related to changes in wealth that stimulate economic activities in peripheral areas. Changes in wealth also increase job creation and provision of services. When these changes occur, people move to urban areas, and permanent migrants sell or abandon their properties (and thus concentrate land in the hands of fewer owners). Indeed, despite the fact that there is no significant difference in deforestation rates between lowland and montane forests, the explanatory factors differ. This circumstance is partly due to Colombian land use and settlement history. For centuries, land use was intensive in the mountains. However, beginning in the second half of the 20^{th} century, the colonisation frontier moved towards lowland areas in the Andean piedmont (Etter *et al.,* 2008). This transition is especially evident in the Andes-Amazonia transition belt.

Higher economic activity, land concentration and centres of development are mainly associated with highlands. In highlands, different types of migratory processes inside the country and a dispersed network of medium-sized cities led to a conformation of cities known as the Andean trapeze. The Andean trapeze is made up of Bogota, Medellin, Cali and Bucaramanga. Together, these four cities comprise almost 75% of the population and of the economy of the country (Galvis, 2001). Around these cities and their areas of influence, forest remnants are located mainly in remote areas (Rudel & Roper, 1997). It is clear that most of the population in these montane areas is concentrated in the urban centres. This concentration is due in part to forced migration that has occurred in the last five decades. The migration has redirected attention toward other kinds of economic activities and has led to an abandonment of agricultural activity. The result is less pressure on forests (Rudel & Roper, 1997). In highland areas, where better conditions for productive activities are usually found, deforestation occurred in the past due to land use changes, e.g., crop intensification. However, deforestation currently occurs in remote areas (i.e., less-accessible areas having steeper slopes). This finding coincides with previously proposed arguments that suggest that at some point, rates of tropical deforestation should decline because a smaller number of forest fragments become increasingly inaccessible in mountain locations (Myers, 1993). Deforestation is pushed to the outskirts of the municipalities in those areas with less road density and higher, steeper slopes. Sometimes, deforestation is also associated with the presence of illegal armed groups or with buffer zones around protected areas that are often located in less accessible and remote districts. This result appears plausible because their lack of access to education gives the people in these areas no alternative to agricultural activities and farming. The absence of alternative economic opportunities in rural and remote areas leads people to exploit natural resources in the remote but still-available montane forest fragments.

The differences between montane and lowland deforestation rates can be further explained by the socioeconomic and demographic activities that occur in the municipalities in each area. Montane areas are at a relatively advanced stage of colonisation, economic development and resource availability. Lowland forests are located in the lower-elevation territories of Colombia and on the colonisation frontier. These areas might be more likely to include growing and mainly rural populations. The development of the colonisation frontier is usually driven by a process of natural resource extraction. The process begins when farmers clear the land. Land clearing is followed by the establishment of cattle grazing as the main economic activity. Therefore, pasture establishment is a clear indicator of colonisation and is followed by the establishment of crops. Higher deforestation rates are also found in the municipalities whose boundaries include recently declared protected areas. Establishment of these protected areas might reflect a positive political response to areas of forest remnants with high pressure. Of course, lowland areas of the Andes have important abiotic differences from highland areas, and the environment is an indirect driver of deforestation. During the initial stages of deforestation (exploitation and establishment of cattle grazing or agriculture), colonists tend to go to available sites that offer the most comfortable environmental conditions. In the lowland Andes, the comfortable areas are those with higher temperatures, along the border of the Amazonian, Pacific and Orinoquian tropical rain forests. Deforestation in lowland forests in Colombia is likely to continue, given the relatively high availability of land in this transition zone. Additionally, lowland forests are becoming increasingly accessible and provide adequate environmental conditions for the cultivation of intensive crops such as yucca, maize and sugar cane that are cultivated mainly for biofuel production.

1.5. CONCLUSIONS

Most models of deforestation do not take into account altitudinal differences. Our study reveals that in mountain areas, this difference might have an important and largely ignored role. The nature of the proposed explanations for deforestation in the Andes and the intraregional differences between montane and lowland forests highlights the need to rethink development planning in the Colombian Andes and allows us to suggest planning and management strategies for these territories. Montane forests can further be preserved by increasing conservation initiatives at all levels and also by the promotion of agroforestry and other types of social forestry practices in rural highland areas of the Andes where most of the population lives. The colonisation front towards the lowland in the Andes, where the highest deforestation rate is currently found, has to be tackled with strong political action through planning schemes that avoid the establishment of settlements and roads in key connectivity areas that could potentially be irreplaceable. Moreover, management should also integrate more rural development plans in already settled or recently settled places and reduce the development of areas with intact large forest fragments.

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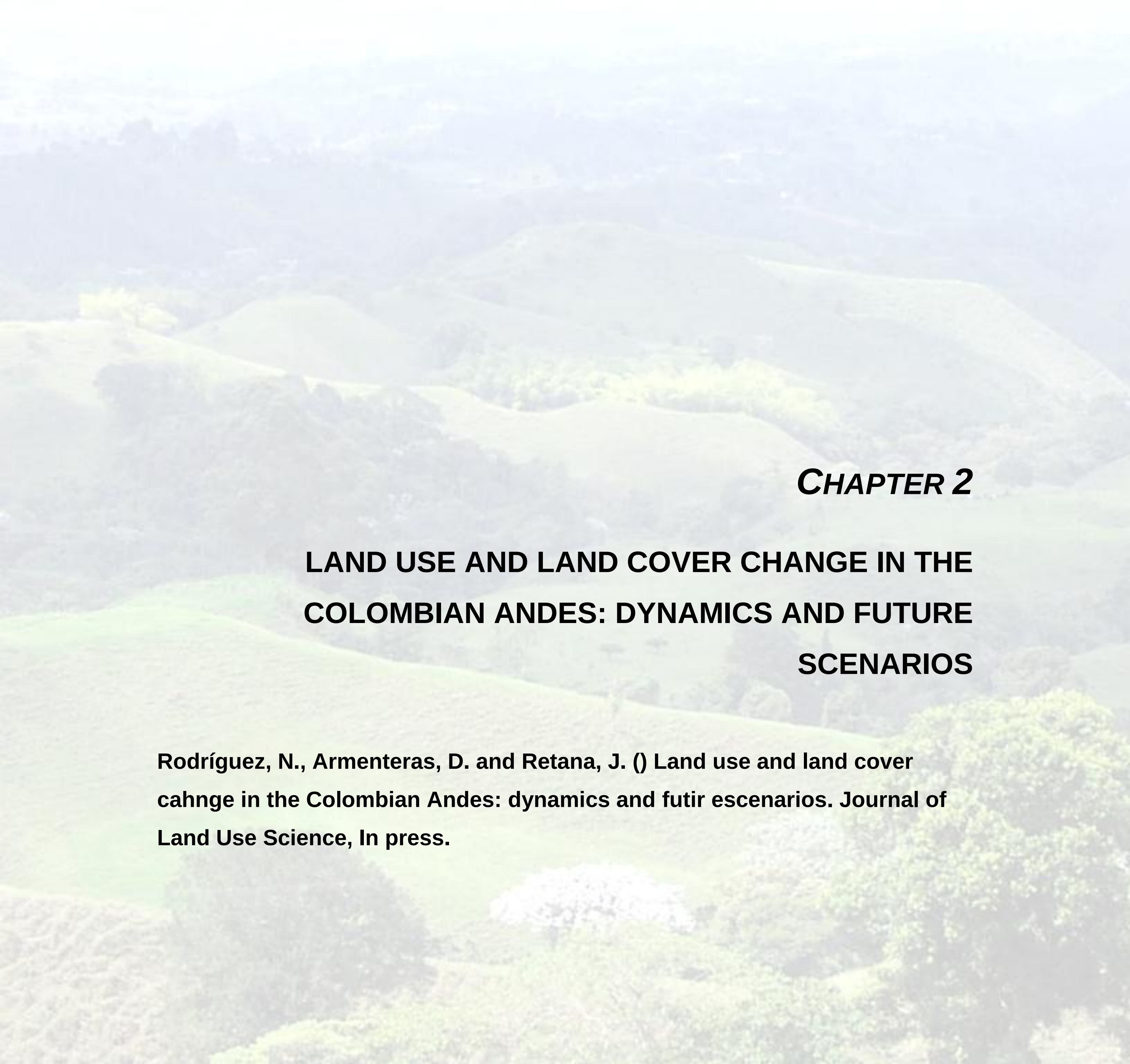

CHAPTER 2

LAND USE AND LAND COVER CHANGE IN THE COLOMBIAN ANDES: DYNAMICS AND FUTURE SCENARIOS

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2. LAND USE AND LAND COVER CHANGE IN THE COLOMBIAN ANDES: DYNAMICS AND FUTURE SCENARIOS

ABSTRACT

Land use and land cover changes (LUCC) are recognised as one of the most relevant drivers of biodiversity loss in ecosystems. Through analysis of satellite images, this paper quantifies land use and land cover changes occurred between 1985 and 2008 in the Colombian Andes. Four submodels of changes were analysed: deforestation, crop intensification, conversion to pastures and abandonment. We associated these changes with demographic, socio-economic and abiotic variables and to some attractors of landscape change, and finally we have considered three scenarios of change: Reference, Increase in Pasture and Crop intensification. The dynamics of LUCC was dominated by systematic transitions between crops, pastures and secondary vegetation. The best transition model that emerged was that of pasture conversion, and the most relevant variables for explaining land cover changes in the region were elevation, soil type and distance to roads, cities and pastures. Our simulations suggest that the pasture conversion scenario would have the biggest impact in natural ecosystems and could cause the loss of 28-30% of the cover area by 2050. The results indicate some that these hotspots of change are currently still under a good conservation state with large extension of forests.

Keywords: Land cover change; deforestation; Land Change Modeller; Drivers of change; scenario analysis; South America

2.1. INTRODUCTION

It is widely accepted that land use and land cover changes (LUCC) have an important effect on both the functioning of the Earth's systems as a whole (Lambin *et al.,* 2001) and on the majority of ecosystems (Hansen *et al.,* 2001; Duraiappah *et al.,* 2005; IPCC, 2007a). Almost 15-20% of the CO2 emissions on a global scale are due to the expansion of agricultural lands and pastures (IPCC, 2000), and it is projected that by 2050, almost 80% of species extinctions will be caused by changes in land cover (mainly deforestation) in the tropical forests and savannas (Sala *et al.,* 2000, 2005). LUCC affect climate change in the long term. Many feedback processes exist between LUCC and the biogeochemical and biophysical processes of the Earth's system, including greenhouse gas emissions, ecological and physiologic processes and the modification of albedo (Foley *et al.,* 2003; Brovkin *et al.,* 2006; Heistermann *et al.,* 2006). LUCC also affects the conservation of essential ecosystem services that maintain the well-being of humans on our planet (Manandhar *et al.,* 2010).

In the last several decades, land use change in tropical forests has increased, and the human footprint in these ecosystems is the largest ever recorded (Asner *et al.,* 2009). The conversion of forests to livestock pastures has been identified as a continuous process in Latin America (Wassenaar *et al.,* 2007; UNEP, 2007), similar to the conversion of other natural ecosystems such as savannas to cropland as a result of the growing world demand for cereals and oils. These activities cause biodiversity loss and modify climate patterns or hydrological cycles, but they are seen as an economic opportunity for local populations because they generate new markets for international trade (Rudel *et al.,* 2009).

Mountain areas are especially vulnerable to global change (Bush *et al.,* 2004), and current studies on the effects of climate change and LUCC in these regions have identified detrimental impacts on ecological and social processes (Beniston, 2003; IPCC, 2007b). Some studies of LUCC in this region have focused on observing local causes of land use and cover change, evaluating their effects on environmental services and making predictions based on different scenarios of global change (Brandt & Townsend, 2006; Etter *et al.,* 2006; Martínez *et al.,* 2009). The development of future scenarios for land use and change should not only include the spatial and temporal patterns of this change, but should also help in the planning and sustainable use of the resources of many tropical countries (Veldkamp & Lambin, 2001). It is important to develop regional models and predictions of change for tropical mountain areas because of their vulnerability to climate change and the strong human influences present (Brandt & Townsend, 2006). Despite the fact that mountain areas in the Andes have supported intensive traditional agriculture for centuries (Sarmiento, 2000), human population growth and economic activity are still factors associated with the deforestation of highlands of many Andean countries (Keese *et al.,* 2007; Kintz *et al.,* 2006; Armenteras *et al.,* 2011).

The Andes region contains more than 100 ecosystem types, 45,000 species of vascular plants (20,000 of them endemic), 3,400 species of vertebrates and the Andes are the home to almost 40 million inhabitants. The region is considered to be a high global priority for the conservation of biodiversity (Myers, 1998). A fundamental obstacle in the studies of LUCC for the Andes has been the lack of spatially explicit regional analyses. The objective of this investigation is to undertake a regional analysis from 1985 to 2000 of LUCC in the Colombian Andes and to explore scenarios of future land use change to 2050. Specifically, this study focuses on: i) quantifying the dynamics and determining the spatial and temporal trends of LUCC, ii) identifying the main transitions among land covers (i.e., sub-models) and their associated drivers and attractors, and iii) making predictions about regional land use and land cover changes under different scenarios proposed by the International Panel on Climate Change (IPCC) until 2050.

2.2. MATERIALS AND METHODS

STUDY AREA

The Colombian Andes region encompasses 287,720 km^2 and is an area of great biological, cultural, social and economic complexity. The region is contained within the Northern Andes ecoregion, which is considered to be among the world's top 200 high-priority places for conservation because of its biological richness and vulnerability to human activities (Mittermeier *et al.,* 1999). The region extends along three mountain ranges: Western, Central and East, with an elevation range between 500 and 5400 m asl. The temperature distribution is related to elevation, with mean annual values of 26-28°C in lowlands, 13-14°C at 2500 m asl and 0°C at 4800-5000 m asl. The distribution of rainfall is influenced by the ITCZ (Intertropical Convergence Zone). The eastern Andes are exposed to trade winds, which create humid and rainy conditions (annual precipitation values of ca. 5000 mm). In the western region (Pacific slope), a Monzonic circulation system produces even more rain (annual precipitation above 5000 mm, with values of 12,000-13,000 mm in some sectors). Finally, the inter-Andean valleys are less humid (annual rainfall of 1000-3000 mm) (Rodríguez *et al.,* 2010).

Historically, the region has hosted intense human activity. Humans have occupied the Colombian Andes since at least 13,000 BP (Van der Hammen, 1992). Etter & Van Wyngaarden (2000) and Etter *et al.,* (2008) found that the Andean ecosystems, along with dry ecosystems, have been those most affected by land use and cover changes since the 1500s. The main drivers of change have been population expansion and intense human activities. In 2000, only 39.5% of the region had natural ecosystems (Rodríguez *et al.,* 2006), including lowland forests, montane forests, paramos and several highly-degraded dry enclaves.

This region is characterised as being the centre of economic activity of Colombia, and contains most of its population (77.4%). The economy of the region mainly depends on the industrial sector, followed by agriculture. Coffee is an important agricultural product along with other crops, such as corn, potato, rice, sugarcane and vegetables. During the last decade, the number of cattle in the region has increased, due to increased availability of pasture. Land tenure is predominantly concentrated in farms smaller than 10 ha. In the region there are 30 natural parks, which encompass 9% of the total Andean region.

LAND USE AND COVER CHANGES

The analysis within this study was based on LUCC maps obtained by classifying 52 Landsat TM and ETM images for the period 1984-1986 (year of reference, 1985) and 1999-2001 (year of reference, 2000) (Rodríguez *et al.,* 2006). The images were co-registered with Landsat ETM images from 2000, orthorectified by the Geographical Institute Agustín Codazzi (IGAC), with quadratic mean errors smaller than the pixel size. Magna Sirgas was used as a reference system. The preparation and classification of the images was carried out with Erdas Imagine software V. 9.1. The images were classified using a mixed method (both supervised and unsupervised). In some cases it was necessary to eliminate clouds and shadows by creating masks and using complementary satellite images for these areas. The percentage of clouds was smaller than 7%. An evaluation of accuracy was undertaken using the methodology proposed by Meindeher (2003). Through stratified sampling based on the proportion of land cover categories, we selected 372 points at random in the study area and then we verified these points from field data (from 2003 to 2004) and checked aerial photographs, SPOT images and information from national and departmental agricultural censuses (Sistema Nacional de Información Agropecuaria, Federación Nacional de Cafeteros). Using the Kappa coefficient, we confirmed that the map from 2000 had an accuracy of 90.4%, while that of the map from 1985 was 83.7%.

The analyses were carried out using the Land Change Modeler (LCM) version for Idrisi Taiga 9. This program, developed by Clark Labs at Clark University (2006), contains tools for land cover change analysis, and allows users to map changes in the landscape, identify land class transitions and trends, and model and predict the environment to create future landscape scenarios that integrate user-specified drivers of change. We analysed LUCC changes among seven categories: montane forest (forest between 1000 and 3200 m asl), lowland forest (forest between 500 and 1000 m asl), paramo (shrub and natural grassland), grassland, annual and permanent crops, secondary vegetation (vegetation in different successional stages) and other (including forest plantations, water bodies, urban areas, bare soil and snow). Cell size was 100 x 100 m. LUCC was evaluated using the transition matrix (the row totals indicate LUCC by category in 1985 and column totals indicate LUCC by category in 2000) through gains and losses, net change (expressed as the difference between gains and losses), persistence (expressed as the permanence of each cover between 1985 and 2000), swap change (expressed as the total change minus the net change for the category) and specific transitions between categories. We evaluated systematic process of transitions in the region using the methodology made by Alo & Pontius (2008). This systematic transition was based on deviations between the transitions observed and the transitions expected owing to random processes of change (Alo & Pontius 2008; Manandhar *et al.,* 2010).

The annual rate of change (rt) for each cover category was calculated as Puyravaud (2003):

$$\mathrm{rt} = \frac{1}{(t_2 - t_1)} \cdot \mathrm{Ln}\left(\frac{A_2}{A_1}\right) \cdot 100$$

where A1 and A2 are the areas (in has) of a cover class at years t_1 (initial time) and t_2, (next time step), respectively.

We identified LUCC hotspots using the change map from 1985-2000. Considering both surface and neighbourhood, we analysed or deforestation hotspots or areas with the most change to natural cover types (i.e., forests and paramos to pastures and agricultural areas).

TRANSITION SUBMODELS AND DRIVERS OF CHANGE

We modelled four transitions or submodels for the region using a Multi-Layer Perceptron (MLP) neural network available in LCM, which is capable of modelling non-linear relationships (Eastman, 2007). By default, the accuracy rate reported by MLP is based on a leave 50% out rule. The submodels were the following (Figure 2.1):

(i) Deforestation submodel, or a conversion from forests to pastures and crops; within this model we separated the deforestation associated to lowland and montane forests.

(ii) Agricultural intensification submodel, or an increase in agricultural activity due to the conversion of secondary land and pastures to crops.

(iii) Abandonment submodel, or a change from agricultural areas to secondary vegetation.

(iv) Pasture conversion, or a change from secondary vegetation to pastures.

For each submodel we considered twenty variables that have previously been reported as possible factors driving land use and cover changes (Armenteras *et al.,* 2011), including demographic, socioeconomic, physical and land use variables, and attractors of change such as distance to fires, roads, cities, forests and pastures (Table 2.1). As MLP requires continuous quantitative variables, we transformed the data of categorical variables using Evidence Likelihood that is an effective way to incorporate them into the analysis. We used the Cramer´s V statistic to test the explanatory power of each variable and select the most relevant ones for each submodel (Eastman, 2007). Once these variables were selected, each submodel was modelled using MLP. They were considered as static components due to extreme computational complexity for processing them as dynamics.

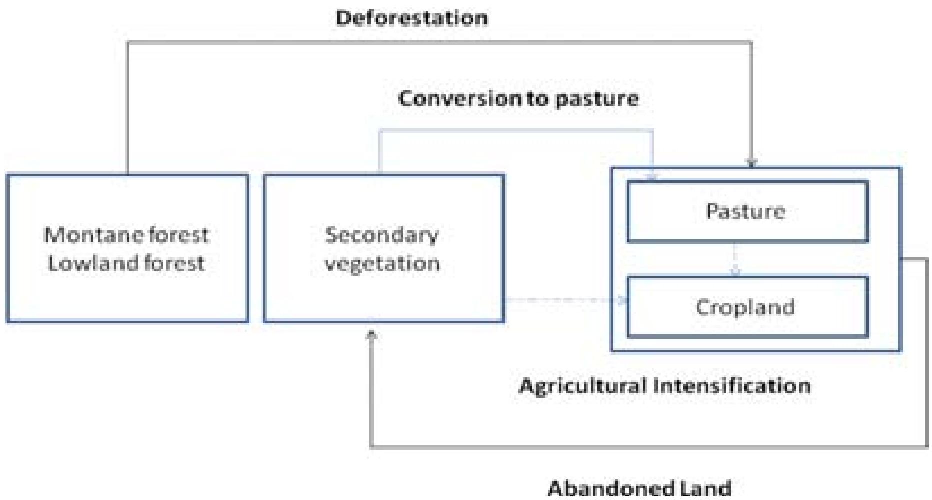

Figure 2.1 Land use and cover transition in Colombian Andes.

PREDICTION OF LAND USE AND COVER CHANGES AND SCENARIOS OF CHANGE

We predicted land use and cover changes based on the results obtained from the sub-model transitions and the analysis of Markov chains, using the year 2000 as the reference date. LCM offers two types of models of change: hard and soft prediction models (Eastman, 2007). In this study, we used the soft prediction model since it offers a more comprehensive assessment of change potential, it also yields a map of vulnerability to change and it is preferred for habitat and biodiversity assessments (Eastman, 2007). To validate the models we used the the methodology proposed by different authors (Pontius *et al.,* 2008; Pontius *et al.,* 2011) consisting in comparing three maps: the reference map of 2000, the reference map of 2008 (map obtained by the IGAC, Instituto Geográfico Agustín Codazzi) and the prediction map for 2008. The three map comparison allows us to distinguish the 2008 agreement due to land persistence versus the 2008 agreement due to land change and gives four types of results: correct due to observed persistence predicted as persistence (i.e. correct rejections), error due to observe persistence predicted as change (i.e. false alarms), observed changes predicted correctly as change (i.e. hits) and finally, error due to observed change predicted as persistence (i.e. misses).

Once we had the calibrated and validated model. We also developed three scenarios of change for the period between 2020 and 2050, with the purpose of exploring regional and global impacts on natural ecosystems: (i) Reference Scenario (RES) where our assumption is that the current pattern of change follows the same Markov's dynamics found for the region during the period 1985-2000; (ii) Increase in Pastures Scenario (IPS), where there is an increase in the number of cattle pastures; and (iii) Crop Intensification Scenario (CIS), where there is an intensification of cropland. These latter two scenarios are based on the IMAGE model (Integrated Model to Asses Global Environment, version 2.2), used to implement the IPCC-MESSRS scenarios (IPCC-SRES, 2000). Based on this model, we assume that there will be an increase in food production to satisfy the growing demand of human populations, which could favour the expansion of pastures for livestock and arable lands at the expense of natural ecosystems (Bouwman *et al.,* 2006).

2.3. RESULTS

LAND USE AND COVER CHANGES

Overall persistence between 1985 and 2000 for the region was 67.4% and 7.6% of the changed area due to an absolute value of net change. Secondary vegetation and pasture are the most dynamic categories in terms of gains (11%) and losses (6.8% and 13% respectively), while pasture showed a net change of 1.6% in the region and swapping change about 23%. Forests and paramos had persistence values over 84% and low proportion of swapping component of change (< 1%), while the rate of forest loss (deforestation) was -0.83%, representing 1.5 million ha of forest lost within the area for the period 1985-2000. The greatest degree of change in lowland forests (deforestation hotspots) was located in the intersection of the Andes with the Amazonia, Orinoquia and Serranía of San Lucas region. In the case of montane forests, the East mountain range was the most affected area (Figure 2.2). Loss of paramos was concentrated in the East Mountain Range (Boyacá and Cundinamarca Departments).

Table 2.1 Summary of the characteristics and origin of the datasets for the variables considered in the LUCC analysis.

Type	Name	Units	Description	Source
Demographic	Total population (Pob)	Number of inhabitants	Absolute change of rural population between 1985-2005	National Administrative Department of Statistics (DANE), 1985 y 2005
	Forced population migration (Desp)	Number of people	Natural logarithm of number of people forced to leave their lands by illegal armed groups or displaced population	Consultoria para los Derechos humanos y el desplazamiento- Codhes, 2005
Socio economic	Economic Activity (Ecac)	Million Colombian pesos	Taxes revenues per municipality, equivalent to tax income in million Colombian pesos in 2005.	National Planning Department (Departamento Nacional de Planeación-DNP, 2005) and the Unified Information System for (Sistema Único de Información de Servicios Públicos-SUI, 2005)
	Unsatisfied basic needs (Nbi)	%	Population with unsatisfied basic needs in 2005, in Latin America, most countries consider as basic needs minimum household conditions, access to sanitary services, access to primary education and minimum	National Administrative Department of Statistics (DANE), 2005
	Mineria (Mi)	ha	Area of mineral concessions	Calculed from map of mineral concessions. Unidad de Planeación Minero Energética (UPME), 2005
Land Use	Protected Area (PA)	ha	Area under special management either under category of national protected area or indigenous reserve	Agustin Codazzi National Institute of Geography (IGAC), 2005
	Private reserve (PR)	ha	Area private under special management for conservation	Resnatur, 2000
	Change 1985-2000 (CH8500)	ha	Likelihood of total change of area between 1985-2000 derived from the satellite image classification	Calculated from Maps of land cover and land use 1985 and 2000

Physical Environment	Digital elevation model (DEM)	m.a.s.l	Altitud values	The Shuttle Radar Topography Misión (SRTM, 90 m resolution)
	Soil drainage (Soildrain)	Type of drainage	Likelihood of measures aiming at controlling a high water table and water logging in the land	IGAC & CORPOICA, 2002
	Soil fertility (EL_solifert)	Types of fertility	Likelihood of the quality of a soil that enables it to provide essential chemical elements	IGAC & CORPOICA, 2002
	Type of soil (EL_Soils)	Kind of soil	Likelihood of type of soil based in USDA classification	IGAC & CORPOICA, 2002
	Slope (Slope)	%	Likelihood to diverge from the vertical or horizontal	Data derived from DEM
	Depth of soil Soildepth)	cm	Likelihood of depth of soil	IGAC & CORPOICA, 2002
	Precipitation (Prec)	mm	Annual precipitation	Calculated from CIAT database, 2000
Attractors	Distance to cities (Dist_cabec)	km	Distance to urban and suburban center existing in the region	Calculated based human settlements map provided by IGAC, 2005
	Distance to focus of fire (Dist_fire)	km	Distance to hotspot fire between 2000-2002	Calculated based Map of urban center provided by IGAC, 2005
	Distance to nearest forest fragment (Dist_forest)	km	Distance to forest existing in 1985	Calculated based Maps of land use and land cover, 1985
	Distance to nearest pasture (Dist_pasture)	km	Distance to pasture existing in 1985	Calculated based Maps of land use and land cover, 1985
	Distance to road (Dist_roads)	km	Distance to road existing in the region	Calculated based road networks map provided by IGAC, 2005

Table 2.2 Transition budget as a percent (%) of study area in different categories of land use between 1985 and 2000. Total change indicates the sum between gain and loss for each category.

Category/Land cover class	Persistence	Gain	Loss	Total change	Swap	Absolute value net change	Loss rate annual
Paramos	4.2	0.1	0.6	0.6	0.2	0.5	-0.6
Montane forest	22.2	0.5	3.3	3.8	0.9	2.9	-0.8
Lowland forest	10.9	0.2	1.8	2.0	0.5	1.6	-0.9
Secondary	5.9	11.1	6.8	17.9	13.6	4.3	1.9
Pasture	19.9	11.4	13.0	24.3	22.8	1.6	-0.3
Cropland	3.3	8.3	5.0	13.3	10.0	3.3	2.2
Other	1.0	1.1	2.2	3.3	2.2	1.1	-3.3
Total	**67.4**	**32.6**	**32.6**	**32.7**	**25.1**	**7.6**	

The transition matrix between 1985 and 2000 (Table 2.2) shows that forests and pastures were the main land cover types in the Colombian Andes, representing 65.2% of the total area in 2000. The two land cover categories that increased from 1985 to 2000 were crops (3.3%) and secondary vegetation (4.3%). Area of pastures decreased slightly from 1985 to 2000, but they were still the dominant land use in the region. Expansion of pastures occurred mainly in the south and the north of the region while pasture loss was distributed uniformly over the entire region (Figure 2.3a). The areas that showed an increase in agricultural activities were associated with the Magdalena Valley in the Eastern Mountain Range and Central Mountain Range (Figure 2.3b). The gains in secondary vegetation were concentrated in three places: the lower part of the Colombian Macizo (Central Mountain Range), the north of Antioquia (Central and West Mountain Range) and the high region of the Eastern Mountain Range (Figure 2.3c). The cross tabulation (gross gains and gross losses by category) identified important exchanges of areas between secondary vegetation and pasture (6.1%) and also cropland and pasture (5.8%).

Table 2.3 indicates that the observed gains are bigger than the expected gains for pasture to secondary vegetation, pasture to cropland, cropland to secondary, cropland to pasture and secondary vegetation to pasture. Cropland, pasture and secondary vegetation represent the dynamics of LUCC in the Colombian Andes and showed systematic process of transitions in the region, it means there is a tendency of systematic interchange between these categories. In other words, there is a systematic transition from pasture to cropland. Cropland was systematically gaining from Pasture and at the same time pasture was also systematically losing to cropland. For forests categories (montane and lowland) observed gains were lower than the expected gains in relation to pasture and secondary vegetation, but there is not evidence of a systematic process.

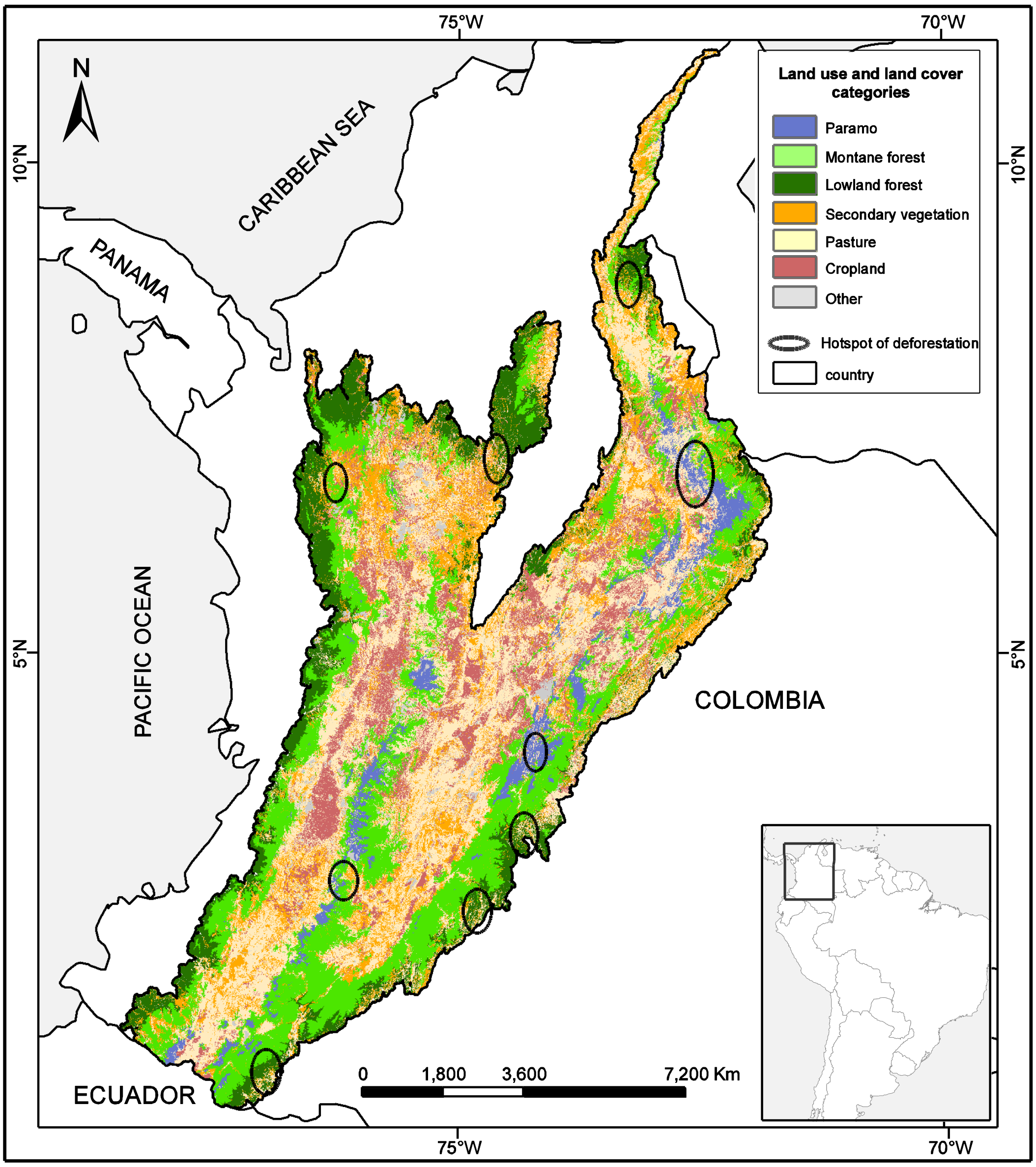

Figure 2.2 Land cover map of the Colombian Andes (year 2000) and identifications of hotspot of deforestation (between 1985 and 2000).

Table 2.3 Transition matrix in the Andean region showing the percentage of the total category observed (in bold), random process of gain (in italics) and random process of loss (in normal font). PA: Páramo, MF: Montane forest, LF: Lowland forest, SV: Secondary vegetation, P: pasture, CR: crops.

	2000								
1985	PA	MF	LF	SV	PS	CR	Other	**Total 1985**	**Loss**
PA	**4.2**	**0.0**	**0.0**	**0.0**	**0.5**	**0.0**	**0.0**	**4.8**	**0.6**
		0.0	*0.0*	*0.6*	*0.8*	*0.4*	*0.1*	*6.2*	*1.9*
		0.1	0.0	0.1	0.2	0.1	0.1	4.8	0.6
MF	**0.0**	**22.2**	**0.0**	**1.6**	**1.3**	**0.3**	**0.1**	**25.6**	**3.3**
	0.0		*0.1*	*3.2*	*4.3*	*2.3*	*0.3*	*32.5*	*10.3*
	0.2		0.5	0.7	1.4	0.5	0.1	25.6	3.3
LF	**0.0**	**0.0**	**10.9**	**1.1**	**0.6**	**0.1**	**0.0**	**12.7**	**1.8**
	0.0	*0.1*		*1.6*	*2.2*	*1.2*	*0.1*	*16.1*	*5.2*
	0.0	0.5		0.3	0.6	0.2	0.1	12.7	1.8
SV	**0.0**	**0.1**	**0.1**	**5.9**	**4.6**	**1.8**	**0.2**	**12.7**	**6.8**
	0.0	*0.1*	*0.0*		*2.2*	*1.1*	*0.1*	*9.4*	*3.6*
	0.4	1.9	0.9		2.6	0.9	0.2	12.7	6.8
PS	**0.1**	**0.2**	**0.1**	**6.1**	**19.9**	**5.8**	**0.6**	**32.8**	**13.0**
	0.0	*0.2*	*0.1*	*4.2*		*3.0*	*0.4*	*27.7*	*7.8*
	0.8	4.3	2.1	3.2		2.2	0.4	32.8	13.0
CR	**0.0**	**0.0**	**0.0**	**1.5**	**3.3**	**3.3**	**0.1**	**8.3**	**5.0**
	0.0	*0.1*	*0.0*	*1.1*	*1.4*		*0.1*	*5.9*	*2.6*
	0.2	1.3	0.6	1.0	1.8		0.1	8.3	5.0
Other	**0.0**	**0.0**	**0.0**	**0.7**	**1.1**	**0.3**	**1.0**	**3.2**	**2.2**
	0.0	*0.0*	*0.0*	*0.4*	*0.5*	*0.3*		*2.2*	*1.3*
	0.1	0.5	0.3	0.4	0.7	0.3		3.2	2.2
Total 2000	**4.3**	**22.7**	**11.2**	**17.0**	**31.3**	**11.6**	**2.1**	**100.0**	**32.7**
	4.3	*22.7*	*11.2*	*17.0*	*31.3*	*11.6*	*2.1*	*100.0*	*32.7*
	5.9	30.8	15.3	11.6	27.1	7.5	1.9	100.0	32.7
Gain	**0.1**	**0.5**	**0.2**	**11.1**	**11.4**	**8.3**	**1.1**	**32.7**	
	0.1	*0.5*	*0.2*	*11.1*	*11.4*	*8.3*	*1.1*	*32.7*	
	1.7	8.5	4.4	5.7	7.2	4.2	1.0	32.7	

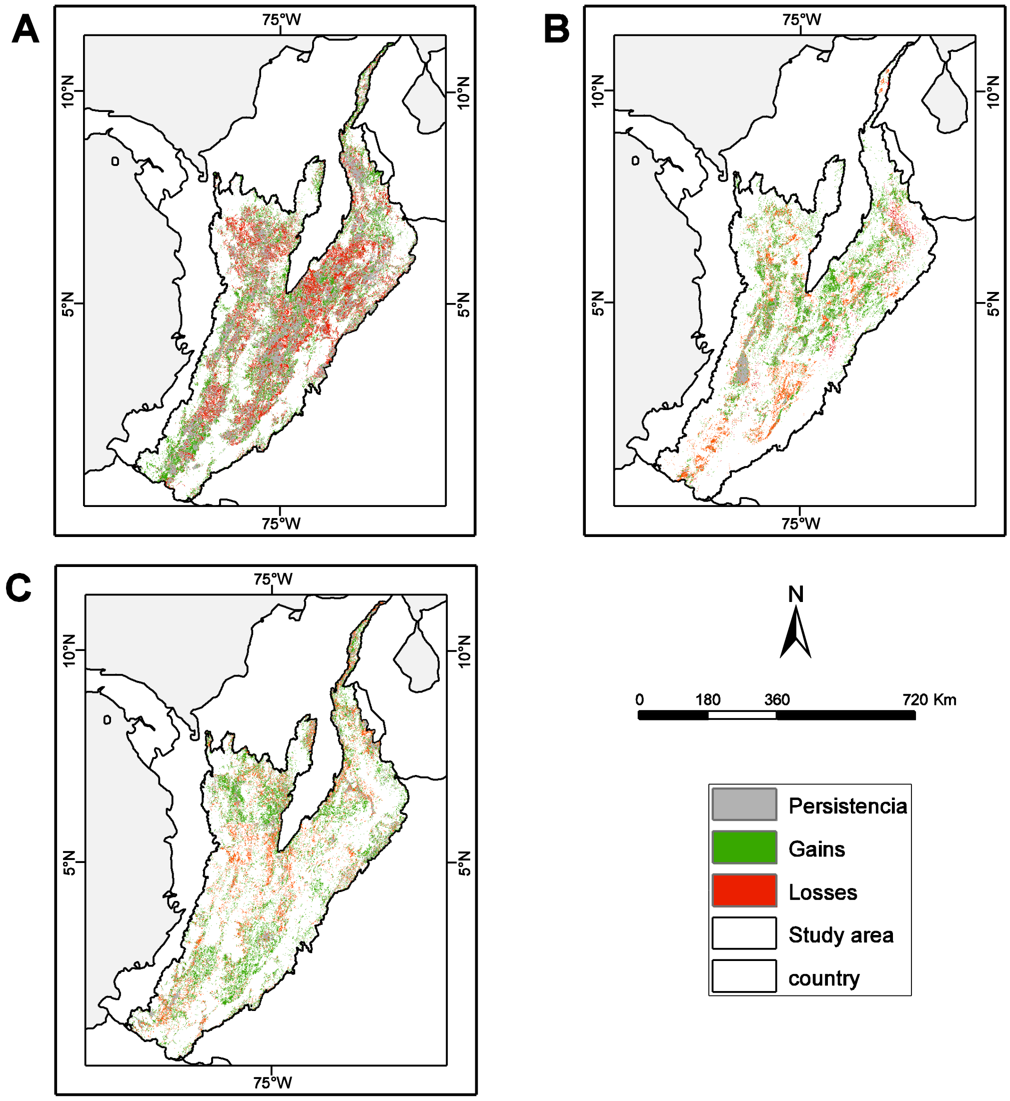

Figure 2.3 Map of gains, losses and persistence of (A) Pasture, (B) Cropland, (C) Secondary vegetation from 1985 to 2000.

TRANSITION SUBMODELS AND DRIVERS OF CHANGE

Table 2.4 describes the results of the different submodels and their main explanatory variables. The lowest accuracy rate (62.2%) was for the Abandonment submodel and the largest value (84.0%) was for the Pasture Conversion submodel. Overall, the most relevant variables explaining land use and cover change in the region were elevation, land type and distances to cities, roads and pastures in 1985 (using the threshold of Cramer statistic >0.15). Variables such as mining, economic activity, unsatisfied basic needs and private reservations were not significant in any submodel (all showed values of Cramer statistic <0.15).

Seven variables were included in the two submodels of Deforestation, with a different emphasis on each (Table 2.4). Deforestation dynamics were strongly affected by all attractors of change, although distance to roads was not significant in the lowlands submodel. For the montane forest model, the most important factors affecting deforestation were distances to roads, cities and pastures, while biophysical variables such as land type and precipitation mostly influenced lowland forests. Population displacement and the presence of protected areas were also significant in those submodels.

The Pasture Conversion model was explained by five variables, with precipitation and elevation being the most relevant ones. In this submodel, as the proximity to areas with pastures in 1985 increased, so did its probability of being transformed into cattle pastures. The submodel of Agricultural Intensification was related to physical environment factors (elevation, soils and slope). Proximity to highways and populated centres emerged as the main drivers of economic development and commercialization of agricultural products in the region. In the submodel of Abandonment, an important variable was forced populations migration, which was also included in the Deforestation submodel.

Table 2.4 Summary of the results for the goodness of fit of the calibration of the neural net in the LCM for the five transition models.

Model	**Principal Factors**	**Accuracy rate**	**Training RMS**	**Testing RMS**
Deforestation Montane Forest	Dist_pasture, Dist_cabec, Dist_road, Dist_forest, EL_soil, Dist_fire, EL_PA, LNDesp, Pecip	75,50	0,4151	0,4138
Deforestation Lowland Forest	EL_soil, Prec, Dist_pasture, EL_PA, EL_soilfert, LNDesp, Dist_cabec, Dist_forest	74,32	0,4239	0,4138
Agricultural Intensification	DEM, EL_soil, Dist_forest, Dist_pasture, Dist_road, Dist_cabec, Dist_fire, EL_slope	67,94	0,4532	0,4531
Conversion a pasture	Prec, DEM, EL_soil, Dist_pasture, Dist_fire	84	0,2507	0,2511
Abandoned	DEM, EL_soil, Dist_road, Dist_cabec, EL_slope, LnDesp	62,20	0,3375	0,3377

Forced population migration (LNDesp), Protected Area (PA), Soil fertility (EL_solifert), Type of soil (EL_soils), Slope (EL_slope), Precipitation (Prec), Distance to cities (Dist_cabec), Distance to focus of fire (Dist_fire), Distance to nearest forest fragment (Dist_forest), Distance to nearest pasture (Dist_pasture) and Distance to road (Dist_roads). Accuracy rate indicates the ability to predict the submodel with the variables used.

SCENARIOS OF CHANGE

The most important component is persistence simulated correctly between reference 2008 and simulation 2008 with a 86.3%, false alarms are 1.7%, hits 0.39% and misses represent 11.5% of the cases. The dynamics of LUCC in the Colombian Andes varied depending on the scenarios considered. Table 5 indicates the percentage of different natural land use areas that could change under each different scenario in 2020 and 2050. All scenarios, including the Reference Scenario (RES), showed considerable reduction in four land covers (montane forest, lowland forest, paramos and secondary vegetation) and increase in pastures. The changes are generally the greatest in IPS scenario and the lowest in the RES scenario. Concerning spatial patterns, most part of the affected area under these scenarios will be the Eastern Mountain Range (Figure 2.4).

The pasture expansion (IPS) scenario had the biggest impact on forests, with losses between 16 and 30%. A similar, albeit lesser, reduction in forest areas was obtained using the crop intensification (CIS) scenario. Paramos showed similar losses in all three scenarios, with the changes concentrated in the Eastern Mountain Range (complex of páramos of Pisba and Cocuy). Losing these high mountain ecosystems could have strong implications for the water supply of the main cities in the region. Under the first and third scenarios (RES and CIS), secondary vegetation was projected to decrease by 4% in 2020, and by a similar or lower value in 2050 (Table 2.5). In the second scenario (IPS) there was a considerable gain in secondary vegetation due to abandoned cattle lands (14% in 2020 and 22% in 2050). This turnover was expected to occur in the lowland areas of Andes, limited by the lowland forests of the Pacific and Amazonia (Figure 2.4).

2.4. DISCUSSION

PATTERNS OF LAND USE AND COVER CHANGE

Recent studies have found that tropical forests are most affected by land use and cover change (CDB, 2010; Geist & Lambin, 2006; Mayaux *et al.,* 2005). In Latin America, land use change displays two patterns: deforestation caused by rising global food demand and increasing numbers of cattle, and the abandonment of agricultural lands, favouring the recovery of ecosystems (UNEP, 2010). Our results indicate that the Colombian Andes, despite having a history of land use from before Prehispanic times, still has almost 38% of its natural ecosystems in the year 2000, even though the deforestation rate is high compared to other countries in South America (0.83%) (Achard *et al.,* 2002). More than 80% of forests have persisted between 1985 and 2000, and the highest deforestation hotspots in the region are located in lowland forests, which are consistent with studies by Wassenaar *et al.,* (2007), Etter *et al.,* (2006) and Armenteras *et al.,* (2011). These studies identified critical points of deforestation in the Napo region along the Ecuadorean border, the lowland forests of the East Mountain Range, and the forests surrounding the San Lucas Mountains (West Mountain Range). These hotspots are associated with cattle expansion and subsistence agriculture that are adapted to prevailing environmental conditions (high precipitation and high slopes) and, in the West Mountain Range, to mining activity, mainly gold production (Orrego, 2009). The East Mountain Range and the Magdalena Valley are the most affected montane forest areas, where deforestation is associated with agricultural expansion. These processes have negative implications for conservation because these ecosystems are considered hotspots of biodiversity (Myers, 1998).

Table 2.5 Percentage of each land cover area that changes in the three scenarios considered (2000 reference): RES (reference scenario), IPS (increase of pastures scenario) and CIS (crop intensification scenario). Positive and negative values indicate increases or decreases in this land cover, respectively, for the corresponding date (either 2020 or 2050).

	RES		**IPS**		**CIS**	
	2020	2050	2020	2050	2020	2050
Montane forest	-5.57	-15.58	-16.29	-28.29	-9.85	-20.24
Lowland forest	-3.91	-14.74	-17.45	-30.16	-8.06	-20.89
Paramos	-6.41	-15.00	-8.04	-15.00	-8.04	-14.02
Secondary	-4.33	-4.30	14.46	22.01	-4.35	-0.84

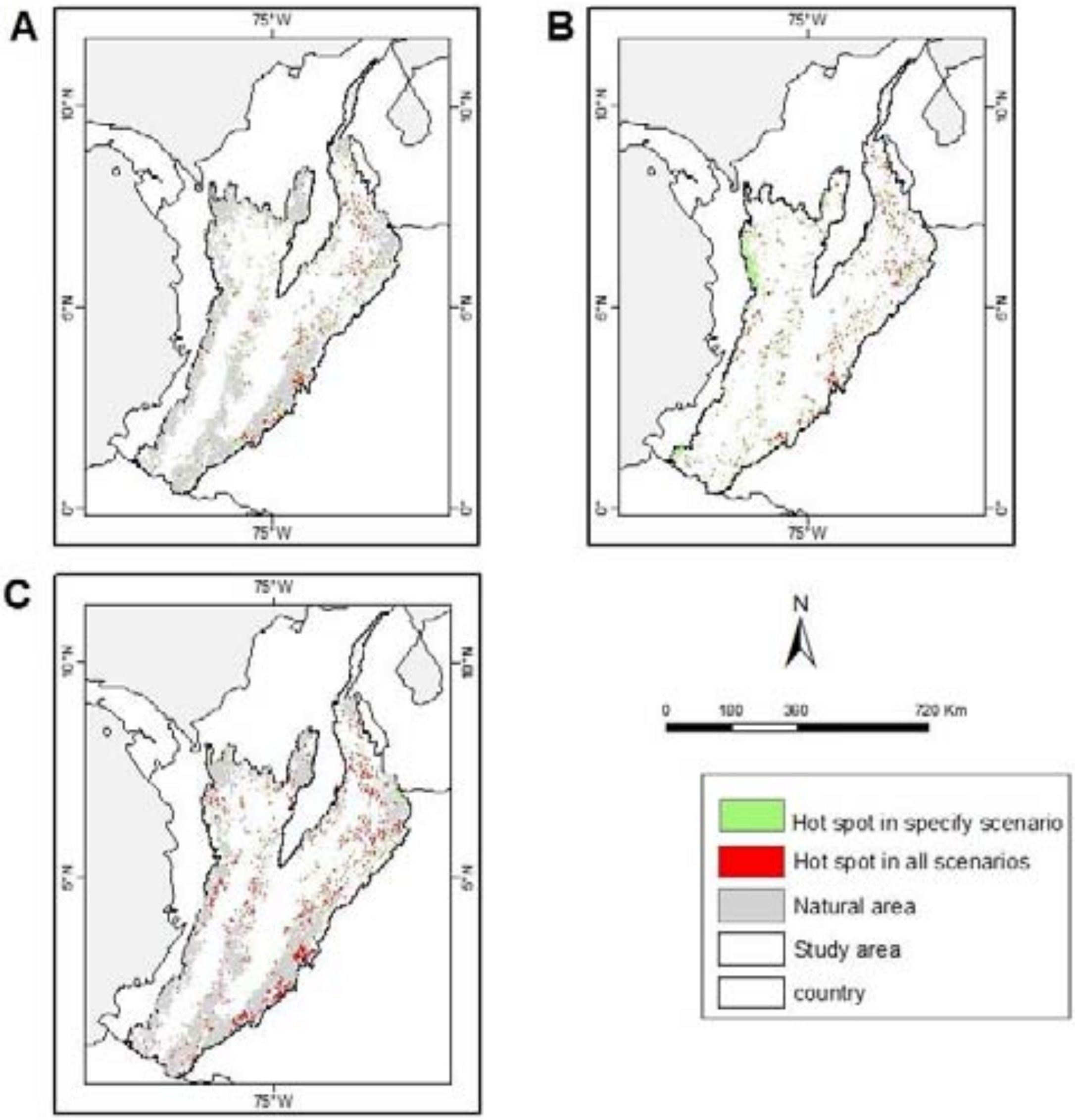

Figure 2.4 Identification of hotspots of deforestation for 2050 (A) RES (Reference Scenario), (B) IPS (Increase in Pastures Scenario) and (C) CIS (Crop Intensification Scenario) in the Colombian Andes.

In addition to this deforestation process, there is also a net gain of secondary vegetation, which is consistent with the trends found in other tropical mountain areas (Redo *et al.,* 2007; Gómez *et al.,* 2006). Secondary vegetation has become an important element of the Andean landscape in recent years, and its increase has been generally associated with areas of forest recovery after continuous selective logging. Secondary vegetation originated from these processes is located in edge areas between the Andes and the low areas of the Amazonia and Magdalena Medio (Figure 2.2). This fact is consistent with the statement outlined by Rudel et al., (2002) that transition forests are generated by emigration. There is also an increase of secondary vegetation due to the abandonment of agricultural areas, although in these cases there is no definitive abandonment of crops but only temporal transition to pasture land.

The replacement of natural cover types by pastures is a historical pattern of land use and change in the Andean region, where livestock is an important socio-economic element. Its expansion is associated with the concentration of large areas to attain resources and to obtain political and economic control (Van Ausdal, 2009). Mahecha *et al.,* (2009) state that the expansion of the agricultural frontier and the establishment of pastures in Colombia have been delayed in areas with socio-political conflicts (as in the transition zones between Pacific, Andes and Amazon where this expansion is associated with secondary vegetation), while livestock has promoted the economy in areas with high income and employment rates (as in the inner part of the Andes, where it is associated with a model of pasture conversion and agricultural intensification).

The Andes region tends to follow a systematic process of transitions, where pastures, croplands and secondary vegetation are systematically replaced by each other. The same process was observed by Wassenaar *et al.,* (2007) for Central America and the tropical part of South America. In the Colombian Andes, this trend is related to the presence of small properties traditionally dedicated to agricultural activities but integrating short periods of rest. Transitions are generally observed in areas with high economic activity and population density (highlands and East Mountain Range).

SUBMODELS AND DRIVERS OF CHANGE

Our study demonstrates the importance of the attractors of change in all submodels, except distance to roads for the submodels of lowland forest deforestation and conversion to pasture. Freitas *et al.,* (2010) indicate that although this variable is a strong predictor of the forest dynamics in the event of deforestation processes, its effect is detected only when agricultural expansion has stabilised over a period of time, as this is the case with montane forests that present the greatest Cramer value for this attractor. Distance to pastures is especially important regarding transitions in the region, suggesting that it stimulates the processes of land use and change and it should be considered in future studies as a dynamic variable.

The results of the deforestation submodels propose a montane forest spatial distribution associated with intensive agriculture. In this case, industries like coffee and cattle farming have economic stability because of the presence of roads and the proximity to intermediate and large population zones. Deforestation in lowland forests depends on the biophysical conditions of the area, particularly fertility, land type and rainfall, and is observed in marginal areas with itinerant farmers. This fact is consistent with the study by Rudel & Roper (1997) and the observations by Koning *et al.*, (1998) in the Ecuadorian Andes. Although many of the social and economic variables were not significant in the deforestation submodels, In Chapter 1 note that some of these variables affect rates of deforestation in the Colombian Andes. The areas surrounding montane forests have exhibited economic consolidation in the past, leaving only forest remnants associated with protected or inaccessible areas, which is a process similar to the classic deforestation pattern found in mountainous areas (Brandt & Townsend, 2006). In this thesis (Armenteras *et al.,* 2011) argue that lowland forest areas in the region have reached different stages of colonization, with growing populations, incipient road development and large land availability. In these areas the illegal coca cultivation increases the probability of forest conversion in the region (Dávalos et al. 2011) and generally this variable is related to forced population migration and unsatisfied basic needs.

The pasture conversion submodel is explained by few variables related to abiotic factors. Although a reduction in pasture area was observed in this region during the period 1985-2000, the number of pastures are expected to increase in Latin America (Brandt & Townsend, 2006; Wassenaar *et al.,* 2007), and particularly in Colombia (Etter *et al.*, 2006, Orrego, 2009). Our results are consistent with those of Orrego (2009), who undertook a study in an area of the Andes and explained that the decline in pastures over a time period similar to ours was due to a transitory decrease in net incomes from livestock.

Population displacement has a particular importance for the submodels of abandonment and deforestation in lowland forests. Kaimowitz & Faune (2003) also indicate that violence has affected population migration, favouring the increase of secondary forests and abandoned lands. Cramer *et al.,* (2008) state that the causes of abandoned lands are a complex mixture between social, economical and ecological factors and that the increase of rural-urban migration is currently a worldwide tendency. In the Colombian Andes, many recovered areas are not influenced by incentives for conservation or the adoption of friendly agriculture techniques for the benefit of biodiversity or market trends, as has occurred in some Central American countries (Lugo, 2002; Redo *et al.,* 2009). Instead these areas respond to socioeconomic events that have occurred in Colombia over the last twenty years.

SCENARIOS AND CONSERVATION IMPACTS

According to our results, the pasture conversion scenario shows a considerably different percentage of forest loss compared to the other two scenarios (almost three times more than RES for 2020), and it is the only scenario in which it is expected an increase in secondary vegetation associated with the Andes-Pacific transition zones. This reduction in forests could have a large impact on the structural and functional connectivity of the region affecting the Andean ecosystem services considered important in terms of biodiversity, water and climate regulation. At the same time, in this scenario the secondary vegetation increases strongly. This increase probably is related to the abandon of cattle and agricultural lands (Abandonment submodel) or to the recovery of forests. The IPS scenario shows two contradictory tendencies: the loss of forests and paramos but also the potential increase of secondary vegetation

The CIS scenario gave intermediate results between RES and IPS for forests and paramos. It is interesting to note that the results of the CIS scenario for agriculture follow the current tendencies of the region (1985–2000), and the absence of tendencies towards an impact for the forests is not clear. In the Andean region, the agriculture at a great scale is already established (coffee, rice and sugar zones) and future agricultural projects will be developed in transformed landscapes or in the borders with other regions of Colombia.

The three scenarios identify very similar areas that will undergo spatial change. Paramos, the Andean forests of the East Mountain Range and the lowland forest of Amazonia and Orinoco are the most vulnerable areas to spatial changes through time. The economic development projected for the country in agro-industrial and petroleum sectors agrees with the zones where changes of future scenarios are more evident (Figure 2.4). In these areas the social and economic dynamics are complex and a further agricultural expansion could have repercussions in the loss of corridors of connection between Andean ecosystems and tropical rainforest ecosystems. The landscapes will be more fragmented than the current ones and the ecological processes related to the maintenance of the function of the ecosystems (regulation, migration and displacement of plants and animals) probably could be interrupted.

The loss of lowland forests will likely occur in buffer areas surrounding several national parks in the Andes-Amazon transition region (Picachos and Alto Fragua, the Eastern Mountain Range) and parts of the Pacific slope (Figures 2.4a and 2.4b). However, the protected areas could be an effective strategy to avoid deforestation and reduce other drivers of change; under this situation the protected areas can be considered as core areas for the connectivity in the region. The loss of paramos will likely lead to declining water resources that affect the water supply for large cities such as Bogotá, where it is concentrated most of the urban population of Colombia (Galvis, 2001). The transition of paramos to pastures and crops such as potatoes will increase the risk of fires and habitat degradation, affecting endemic species and increasing the vulnerability of these high mountain ecosystems (Pauli *et al.,* 2005).

The capacity of the Andean ecosystems to adapt to changes under the proposed scenarios, together with the effects of the climate change, can cause potential impacts over hydrological, ecological and social systems in mountain regions in the area (Rodríguez *et al.,* 2010; Beniston *et al.,* 2003; IPCC, 2007c). Social and political decisions will have a decisive role in determining the most appropriate schemes and strategies of land use where a balance is desired between conservation and development. Although trends of forest and paramos loss will continue in the future, current policy actions such as restricting mining projects in these areas or the adoption of REDD projects will be reflected in the medium term.

2.5. CONCLUSIONS

Our research shows that about 33% of the study area experienced a transition from one category to a different category during the 15-year accounting period and about 25% is attributable to swap change. The categories of cropland, pasture and secondary vegetation present systematic transitions as a traditional practice of land use in the region. The transition trends of LUCC in the Andes vary spatially in the region and that they are mainly related to attractors of change and biophysical characteristics. LUCC dynamics studies in the Andes should always consider the high intraregional variability in the region, including multiple factors and socio political context in order to implement management strategies directly tackling the LUCC transitions likely to occur in a specific area. These results show that certain areas without any doubt will experience change, and in these areas the land use planning must be a goal for the decision makers taking into consideration all conservation of biodiversity, land management, protected areas management and development models across different sectors.

The adoption of appropriate strategies in land use must consider the dynamics of LUCC and the interactions between ecological, social and economic system of the region. Concepts such as planning sustainable landscape associated with ecological network may be an appropriate way to work, which aims to identify important areas for the maintenance of ecosystem services in agricultural or livestock matrix. Some areas which currently represent remnant corridors of connection between lowland and montane ecosystems may experiment land use change in a future associated with deforestation. In these areas we suggest strong political actions including the declaration or expansion of buffer areas around protected areas or incentives that reduce the pressures for change, such as REDD schemes.

Finally, further studies of LUCC in the region should focus on identifying intra-regional differences to capture the complexity of land use change, the systematical transition processes and the assessment of intensity of land use that are relevant for the landscape planning. In the same way, to understand the abandonment submodel and the secondary vegetation dynamic is a challenge of investigation, which will permit to evaluate the ecological importance of these components related to the conservation and the ecosystem services maintenance.

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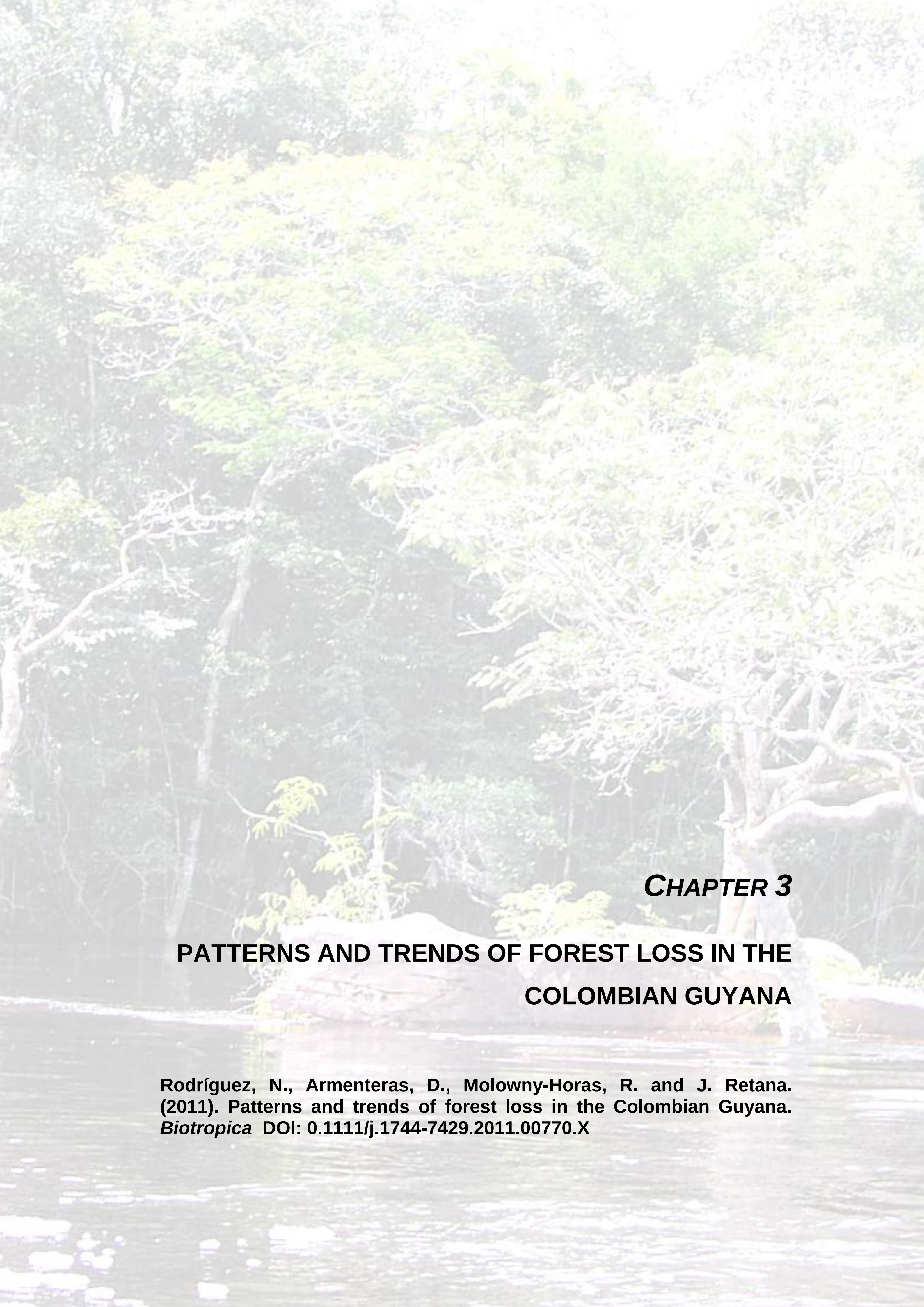

CHAPTER 3

PATTERNS AND TRENDS OF FOREST LOSS IN THE COLOMBIAN GUYANA

Rodríguez, N., Armenteras, D., Molowny-Horas, R. and J. Retana. (2011). Patterns and trends of forest loss in the Colombian Guyana. *Biotropica* DOI: 0.1111/j.1744-7429.2011.00770.X

3. PATTERNS AND TRENDS OF FOREST LOSS IN THE COLOMBIAN GUYANA

ABSTRACT

Spatial patterns of tropical deforestation and fragmentation are conditional upon human settlement characteristics. We analyze four different human occupation models (indigenous, colonist frontier, transition and established settlement) in the Colombian Guyana Shield at three different times: 1985, 1992 and 2002, and compared them for: (1) deforestation rates; (2) the amount of forest as classified according to a fragmentation pattern (interior forest, edge forest, perforated forest and forest patch); (3) various fragmentation metrics using repeated measures analysis of variance; and (4) potential future deforestation trends though the implementation of a spatially explicit simulation model. The indigenous and colonist frontier occupation models had low rates of deforestation (0.04%/yr), while the well-established settlement occupation model had the highest rate (3.68%/yr). Our results indicate that the four occupation models generate three deforestation patterns: diffuse, which can be subdivided into two subpatterns (indigenous and colonist), geometric (transition) and patchy (established settlement). The area with the established settlement model was highly fragmented, while in the transition occupation area, forest loss was gradual and linked to economic activities associated with the expansion of the agricultural frontier. The simulation of future trends revealed that indigenous and colonist areas had a constant, albeit small, loss of forest covers. The other models had a deforestation probability of 0.8 or more. Overall, our results highlight the need for new and urgent policies for reducing forest conversion that consider intraregional variability in human occupation linked to differences in land-use patterns.

Keywords: deforestation patterns; regional variability; spatial configuration; temporal change; tropical rain forest.

3.1. INTRODUCTION

Global deforestation is recognised as one of the core problems of global environmental change (Cassel-Gintz & Petschel-Hels, 2001; Klepeis & Turner, 2001). It drives species extinction and habitat destruction and affects carbon emissions and climate change on several scales (Sala *et al.,* 2000; Houghton, 2003; Foley *et al.,* 2005). The effects of deforestation and fragmentation on forest composition, structure and function are widely known (Burke & Nol, 2000; McMahon & Cuffney, 2000; Laurance *et al.,* 2002a, b), and include species mortality, changes in trophic interactions and increased susceptibility to logging, fires and invasive species (Sala *et al.,* 2000). In addition, deforestation changes the landscape configuration thus affecting the ecological processes of an area (Skole & Tucker, 1993; Turner *et al.,* 2001; Peres *et al.,* 2010). A close relationship between deforestation and forest fragmentation has been established, and ecosystem degradation and patch characteristics have been shown to be associated with the degree of fragmentation (Mertens & Lambin, 1997; Roy & Tomar, 2000).

The most common causes of deforestation are land-use change driven by increasing demand for agricultural land and timber from tropical forests (Geist & Lambin, 2001; Rudel, 2007; Rudel *et al.,* 2009). The spatial patterns of deforestation and fragmentation are conditional upon human settlement characteristics and land-use history (Lambin & Ehrlich, 1997; Steininger *et al.,* 2001; Barbosa & Metzger, 2006; Rudel, 2007), and appropriate conservation strategies depends on the historical deforestation processes (Ferraz *et al.,* 2009). Many land cover change models erroneously assume that changes in land cover occur in a spatially homogeneous manner across landscapes and regions (McDonald & Urban, 2006). Different models have analyzed the occupation of tropical forests using ecological, economic and social variables (Perz & Skole, 2003; Margulis, 2004) at different spatial scales (Laurance *et al.,* 2002a, b), and all have shown unique intraregional patterns of deforestation and land-use change.

Studies of the spatial patterns of deforestation in the Amazonian region suggest that occupation processes and the spatial configuration of the landscape are heterogeneous in both time and space (Soares-Filho *et al.,* 2001; Armenteras *et al.,* 2006; Arce-Nazario, 2007; Fearnside, 2008).

In recent years, several studies of patterns of land-use change in the Andean, Caribbean and Amazonian regions have shown that differences in biophysical characteristics can influence land-use patterns (Armenteras *et al.,* 2003; Viña *et al.,* 2004; Etter *et al.,* 2005, 2006a). Few studies, however, have identified the spatial patterns of deforestation and fragmentation and analyzed the temporal dynamics of the landscape in regions such as the Guyana Shield. This region, a priority for conservation because of its highly diverse and endemic biota, has been known for its low deforestation rates (Ter Steege *et al.,* 2000), though the extent of land-use change, deforestation and ecosystem fragmentation has increased in recent decades (Rodriguez *et al.,* 2006). The lack of long-term information on these topics limits our knowledge of the changes in the region under different land occupation circumstances, which can greatly differ between indigenous and colonization land-use patterns.

The objective of this paper is to analyze the spatial and temporal variability of deforestation patterns among different human occupation models associated with different land-use characteristics determined by the presence of indigenous or colonist populations in the Colombian Guyana Shield. In particular, we consider four common occupation types in the region that differ in a wide range of economic, political and demographic factors. For each model, we determine: (1) the rate and overall percentage of deforestation; (2) the pattern of fragmentation; and (3) potential future trends of deforestation. We used multi-temporal satellite images from three dates from 1985 to 1992 and 1992 to 2002. Furthermore, to estimate the amount of forest that will potentially be lost in areas in the future, we used a cellular automata approach.

3.2. MATERIALS AND METHODS

STUDY AREA

The study area (80,527 km^2) is located between the Amazon River and Orinoco basin and belongs to the western province of the Guyana phytogeographic region. It includes the department of Guaviare and portions of the Caqueta, Guainia, Vichada and Meta departments (Fig. 3.1). The region has an average altitude of 100–200m with occasional isolated hills and low ‘tepuis’ (i.e., table mountains with shrub and savannas) up to 800m in height. The climate of the area is tropical, very humid, has only one period of rainfall (2800–3500 mm/yr) and an average temperature of 24.5 ºC.

It has high floristic and ecological complexity as a result of geological, topographical, soil and water gradients (Daly & Mitchell, 2000). Vegetation types found include white sand vegetation, flooding forests and several tropical rain forest systems. The region is rich in biodiversity and the high species endemism of its associated vegetation types.

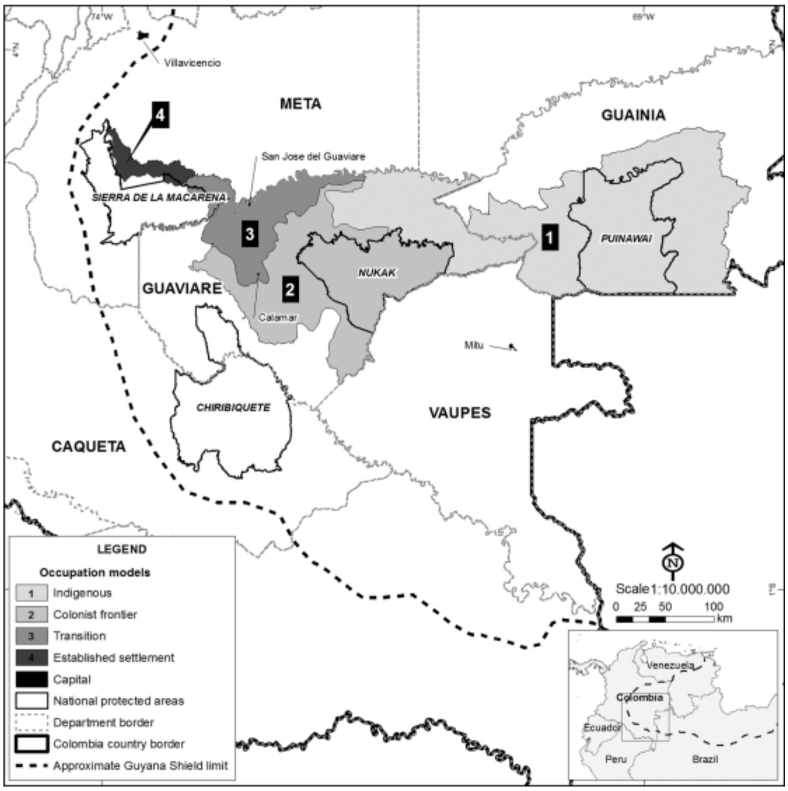

Figure 3.1 Location of the study area and distribution of the human occupation models.

There is a west to east gradient of human settlement across the study area with the west being largely developed, leading eastwards through a colonization front to indigenous dominated regions in the eastern extremity. This region contains 30 indigenous reservations, which make up almost 31 percent of the study area. Land-use changes in the region are mainly related to the extraction of natural resources (Ariza *et al.*, 1998) followed by the establishment of pastures and crops. The occupation process follows the course of navigable rivers and roads. Illicit crops (e.g., coca) have been one of the main economic drivers of this region in recent decades (United Nations Office on Drugs and Crime –UNODC, 2006) and have been found to be a significant factor in land-use change (Armenteras *et al.*, 2009). Livestock grazing and pasture lands are mainly concentrated near municipalities with ongoing infrastructure and road development.

Occupation models

Based on the knowledge of regional experts regarding historical occupation processes and the influence of driving forces of landscape change (Bartel, 2000), our hypothesis is that attractors (roads originating in the colonization front and rivers) influence the way occupation is undertaken in a region. From this approach, we delimited four subregions in our study area that correspond to four common occupation models: *indigenous, colonist frontier, transition* and *established settlement*. We characterized these models by a series of social, economic, demographic and historical factors following similar methodological approaches to those described by Geist & Lambin (2001). The first model, the *indigenous model*, corresponded to areas associated with traditional indigenous agriculture (shifting). This model is characterized by continuous rotation on small parcels near rivers, and most of the territory falls under the legal status of indigenous reserves with settlements of less than a few hundred people per site (Instituto Geográfico Agustín Codazzi –IGAC, 2008). The *colonist frontier model* was also associated with shifting subsistence agriculture and low densities of human settlements compared with permanently settled areas. It is composed of small properties irregularly distributed over an area with land tenure. The *transition model* was associated with the transition from colonist to permanent settlements, which was characterized by large livestock production; in peripheral areas, the expansion of the human frontier was influenced to a lesser extent by coca crops. Finally, the fourth subregion, *established settlement*, refers to large established cattle ranches with a well-developed infrastructure, roads and populated areas.

Regional and local deforestation and fragmentations patterns

We used land cover information from supervised classification of yearly Landsat TM and ETM satellite images. Each image was registered to a base of Landsat ETM images for the year 2000, which were georegistered, using 1:100,000 topographic maps of the Geographic Institute of Colombia. The RMS error was less than one pixel. Land cover was classified using ERDAS Imagine V8.7 (Erdas Inc, Atlanta, Georgia, U.S.A.). We obtained 11 classes, which were reclassified into three classes following the previously applied methodology in the area (Armenteras *et al.*, 2009): forest (including forests and small areas with shrub and savannas), nonforest (pastures, crops and infrastructure) and water (rivers and lakes). The final accuracy, carried out only for the 2002 map, was 95 percent, calculated using the methodology described by Meidinger (2003), which is based on evaluating the quality of the map using field data and visually checking the map with aerial photographs and SPOT images. We carried out fieldwork to verify the land cover classes in two of the occupation models.

The study was carried out at the regional scale (which considers the whole area that corresponds to each occupation model) to establish the general context of the analysis and to identify intraregional differences among occupation models. Furthermore, we randomly selected seven 2500 ha (5 X 5 km) windows for each subregion, termed local scale, to analyze differences among occupation models in landscape structure.

Deforestation rates were calculated using the relationship of Puyravaud (2003):

$$\text{Change rate} = \frac{1}{(t_2 - t_1)} \cdot \text{Ln}\left(\frac{A_2}{A_1}\right) \cdot 100$$

where A_1 and A_2 are the forest areas in hectares at years t_1 and t_2, respectively (*e.g.*, for the period 1985-1992, A_1 and A_2 are the forest cover values in 1985 and 1992, respectively).

To evaluate fragmentation, we used the forest fragmentation model of Riitters *et al.,* (2000) and Riitters & Coulston (2005), which classifies each pixel according to its state of fragmentation using two parameters: Pf, which is the amount of forest (values between 0 and1; 1 indicates 100% forest), and Pff, which is related to the probability (values between 0 and 1) that a pixel has another forested pixel as a neighbour. By resampling the land cover map to pixels of 250 m x 250 m using a mobile window of 5 x 5 pixels, we obtained four categories of fragmentation: a) interior forest (all pixels surrounding the central pixel are forested, and both Pf and Pff = 1); b) edge forest (the majority of pixels around the central pixel are forested, but the central one may be a fragment or an edge, so that Pf > 0.6 and Pf-Pff < 0); c) perforated forest (the majority of pixels around the central pixel are forested, but the central one belongs to a group of patches or edges; Pf > 0.6 and Pf–Pff > 0); and d) forest patch (the central pixel is part of a fragment of forest included in a matrix of non-forest, Pf < 0.4).

We also used the following metrics that were computed for the entire study area and for each of the windows separately for the three dates studied: (A) number of patches (NP), patch density (PD), mean patch size (MPS) and largest patch index (LPI) as measures of the degree of fragmentation (Barbosa & Metzger, 2006; Cayuela *et al.,* 2006); (B) Euclidean nearest neighbor distance-areaweighted mean (ENN) as a measure of proximity; and (C) cohesion (COH) and aggregation index (AI) as measures of connectivity and adjacency of the transformed matrix, respectively. These metrics were computed using Fragstats v. 3.3 (McGarigal & Marks, 1995).

STATISTICAL ANALYSIS

Differences in deforestation rates and the effects of the occupation models for each year on the extent of forest classified according to its rate of deforestation and on the various fragmentation metrics were evaluated with a repeated measures analysis of variance test. To normalize the data, the metrics PD, LPI and COH were log transformed. Statistical analyses were carried out using SPSS v. 16.0.

MODELLING DEFORESTATION TRENDS

A simulation model based on cellular automata, which analyzes land cover change relationships among neighboring areas to predict future changes (Soares-Filho *et al.,* 2002), was implemented in Microsoft Visual Basics 6.0.

Throughout the simulation it was assumed that: (1) deforestation is spatially autocorrelated with transportation networks and other areas of recent deforestation (*i.e.,* attractors sensu Bürgi *et al.,* 2004); (2) deforestation rates as a function of distance were constant during the 50-yr time period; (3) deforestation rates were calculated from the more recent 1992–2002 period only, which arguably more accurately describes the current deforestation dynamics taking place in the area; (4) total deforested area during one 10-yr time step was the same as total deforested area during the 1992–2002 period; (5) regeneration rates were assumed to be negligible within the four regions during the 50 yr of each model run; (6) deforestation processes were bounded to each of the four regions separately; and (7) one occupation model did not change to another during the simulated time span.

The model first estimated the amount of deforestation from 1992 to 2002 as follows: (A) a map of recently deforested pixels was calculated by comparing the 1992 and 2002 maps (*i.e.,* only pixels that had changed state were retained); (B) those pixels were then grouped into separate patches that consisted of pixels that shared one side or vertex (*e.g.,* all pixels within one patch were in side-toside or vertex-to-vertex contact); (C) each separate patch was inspected to see whether there were any river, road or previously deforested pixels (during the 1985–1992 period) at a distance of one or two pixels, or more, from the border of the patch; and (D) a table was created in which the complete distribution of those patch areas was stored as a function of three distance categories (*e.g.,* one, two or more than two pixels away), creating a distance-dependent lookup table of patch areas.

Next, simulated maps were calculated every 10 yr using the previous map and the look-up table of patch areas already computed. The simulated maps were created as follows: (A) a forested pixel was chosen at random from the image, and its proximity to rivers, roads and previously deforested pixels was assessed; (B) according to that proximity, a patch area was chosen randomly from the look-up; (C) the pixels contiguous to the original forested pixel were deforested uniformly until the total area matched that of the chosen patch; and (D) the algorithm picked another forested pixel and repeated steps (A), (B) and (C) until the total deforested area in the image approximately equaled the total area deforested from 1992 to 2002 for that distance category.

One whole model run consisted of a 50-yr simulation with time steps of 10 yr. The output of the model includes maps of forested and deforested areas for each of the four occupation models and the total number of forested and deforested pixels for each distance category. Monte Carlo simulations were carried out to estimate the degree of uncertainty associated with independent model runs. Maps of mean deforestation probability in 50 yr were subsequently computed as the arithmetic average of 1000 simulations. We also evaluated future mean trends in deforestation every 10 yr. Values close to one in the final probability maps pinpoint locations that will very likely suffer deforestation during a 50-yr time interval. Values close to 0, on the other hand, indicate pixels that will probably remain forested.

3.3. RESULTS

REGIONAL AND LOCAL DEFORESTATION RATES

Across the entire study area, there was an overall loss of 347,406 ha of forest between 1985 and 2002 (rate = 0.25%/yr). In 1985, 59.5 percent of the area classified as established settlements was covered by forests, while 82.9 percent of the area defined as transition was forested; the other two models (indigenous and colonist frontier) were 99.6 percent forested. There was substantial variability in annual deforestation rates among the four subregions across the 17 yr of the study: 0.04 percent/yr for the indigenous occupation region, 0.17 percent for the colonist frontier area, 1.99 percent for the transition subregion and 3.68 percent for the established settlement area. Higher deforestation rates were observed in the period from 1992 to 2002 (0.33%/yr) than in the period from 1985 to 1992 (0.14%/yr).

At the local scale, there were significant differences in forest loss among occupation models ($F = 8.0$, $P = 0.001$) and between time periods ($F = 5.7$, $P=0.025$). The interaction between these two variables was also significant ($F = 3.1$, $P=0.045$). Deforestation rates were lower during the first period than during the second period in all four occupation models. Both indigenous and colonist frontier subregions showed low deforestation rates (<01.3%) during both periods, while high rates (>4.5%) were observed for the transition occupation model; the area with the established settlement had a low rate of deforestation during the first period and the highest rate during the second period. Little to no forest regeneration (*i.e.,* increase in forest) occurred in either of the two time periods and was therefore neglected in the simulation model.

REGIONAL AND LOCAL FRAGMENTATION PATTERNS

In 1985, 87 percent of the study area was classified as interior forest, 8.7 percent as edge forest, 2.8 percent as perforated forest and 1.4 percent as forest patches. The indigenous, colonist frontier and transition occupation models had the greatest percentage of interior forest (Table 3.1), while the major category in the established settlement model was edge forest (37%). From 1985 to 2002, the interior forest category decreased in area by 56 percent in the established settlement occupation model and by 71 percent in the transition model (Table 3.1). In both the indigenous and the colonist frontier occupation subregions, interior forest decreased by between 2.5 and 12 %. The area of edge forest decreased by almost 50 percent in all of the occupation models while the area of perforated and patch forest categories increased considerably, especially in the occupation models more associated with the presence of colonists and indigenous groups. An exception was the perforated forest category in the settlement establishment area.

At the local level (seven windows for each subregion), window analysis results indicated significant differences both for occupation model and for year. The interaction between occupation model and year was significant for all forest categories except the forest patch category; these comparisons indicate that the variability in change rates were similar among the four occupation models in both time periods. In the interior forest category (Fig. 3.2a), the greatest forest loss occurred during the second period of analysis (1992–2002), with annual rates >13 percent in the transition occupation model and the established settlement areas. Most of the forest area in the indigenous and colonist frontier consisted of edge forest in 1985 and 1992 but increased moderately (transition) or even decreased (established settlement) in 2002. Edge forest area was three times greater in the indigenous and colonist frontier models in the second time period than in the first time period (Fig. 3.2b). The area of perforated forest (Fig. 3.2c) increased over time in the indigenous and colonist frontier models and decreased in the two models associated with more established settlements in 2002. Finally, the forest patch category had annual change rates of <1.7 percent, which were not significantly different among the four occupation models (Table 3.2).

The two factors considered occupation model and year, showed significant differences in the various landscape metrics used except for NP, PD and ENN, while the interaction of the two factors was significant for all of the metrics except AI. The NP and PD metrics showed similar trends through time, increasing in the transition and established settlement models and remaining low in the indigenous and colonist frontier models (Figs. 3-3a and b). The LPI was high and fairly constant in the indigenous and colonist frontier occupation models, while in the models with a more permanent population, these values were low and decreased from 1985 to 2002. The COH decreased in the transition and established settlement models, while the values were more constant but higher in the indigenous and colonist frontier models. The ENN was highly variable among models and years, with increasing differences among models through time and higher differences between forest fragments among years in the models associated with more established settlements (Fig. 3.3e).

Table 3.1 Number of hectares and percentage corresponding to the different categories of forest fragmentation in the four human occupation models in 2002 and in 1985.

Categories of forest fragmentation	**Established settlement**		**Transition**		**Colonist frontier**		**Indigenous**	
	2002	1985	2002	1985	2002	1985	2002	1985
Interior forest	11,887 (19.7)	26,993 (28.1)	84,362 (18.4)	299,106 (46.1)	1,062,118 (83.8)	1,207,875 (92.3)	4,380,637 (91.2)	4,483,550 (92.8)
Edge forest	9,506 (15.9)	35,525 (37.0)	86,318 (18.8)	231,756 (35.7)	46,081 (3.6)	82,400 (6.3)	108,362 (2.3)	244,493 (5.1)
Perforated forest	15,931 (26.6)	15,750 (16.4)	182,456 (39.8)	74,606 (11.5)	144,037 (11.4)	16,800 (1.3)	289,212 (6.0)	90,181 (1.9)
Patch forest	22,687 (37.9)	17,868 (18.6)	105,162 (22.9)	43,437 (6.7)	14,556 (1.1)	1,825 (0.1)	23,306 (0.5)	15,018 (0.3)
Total	60,011	96,136	458,298	648,905	1,266,792	1,308,900	4,801,517	4,833,242

Table 3.2 Effects of human occupations model type and year (repeated measures) on the different categories of forest fragmentation. NS, not significant.

Variable	**Human occupation model (HOM)**		**Year**		**HOM x Year**	
	F	P-value	F	P-value	F	P-value
Interior forest	49.5	<0.001	61.29	<0.001	5.3	0.006
Edge forest	1.06	NS	0.13	NS	23.2	<0.001
Perforated forest	1.38	NS	0.34	NS	10.7	<0.001
Patch forest	21.6	<0.001	13.0	0.001	2.2	NS

Table 3.3 Effects of human occupation model type and year (repeated measures) on the variables used to characterise fragmentation patterns. To normalise the data, the metrics PD, LPI and COH were log-transformed. NP: number of patches, PD: patch density, LPI: largest patch index, ENN: Euclidean nearest neighbour distance-area-weighted mean, COH: cohesion, AI: aggregation index. Ns, not significant.

Variable	Human occupation models (HOM)		Year		HOM x Year	
	F	P-value	F	P-value	F	P-value
NP	2.5	Ns	0.9	Ns	8.2	<0.001
PD	2.7	Ns	1.1	Ns	11.9	<0.001
LPI	44.1	<0.001	75.3	<0.001	2.7	0.023
ENN	1.0	Ns	0.0	Ns	3.1	0.046
COH	19.7	<0.001	29.9	<0.001	4.7	0.001
AI	8.7	<0.001	36.1	<0.001	0.8	Ns

EXPECTED TRENDS IN DEFORESTATION

The probability maps for the indigenous and colonist frontier occupation models depict a similar pattern of deforestation that takes place mainly along rivers (Figs. 3.4a and 3.4b). Deforestation probabilities in pixels close to rivers and roads, however, were noticeably higher in the colonist frontier than in the indigenous models. The indigenous area showed a low deforestation probability (0.01) in 77 percent of the reserve for the next 50 yr, which suggests that the processes that shape the dynamics of the indigenous territory are markedly different from those in the other three areas. Figure 3.4c, on the other hand, reveals that the transition occupation model will rapidly expand into the surrounding forests; approximately 40 percent of the 2002 forest area has a deforestation probability of 0.8 or more. Finally, the probability of suffering deforestation in the next 50 yr is exactly 1 for all forest pixels in the well-established settlement regions (Fig. 3.4d).

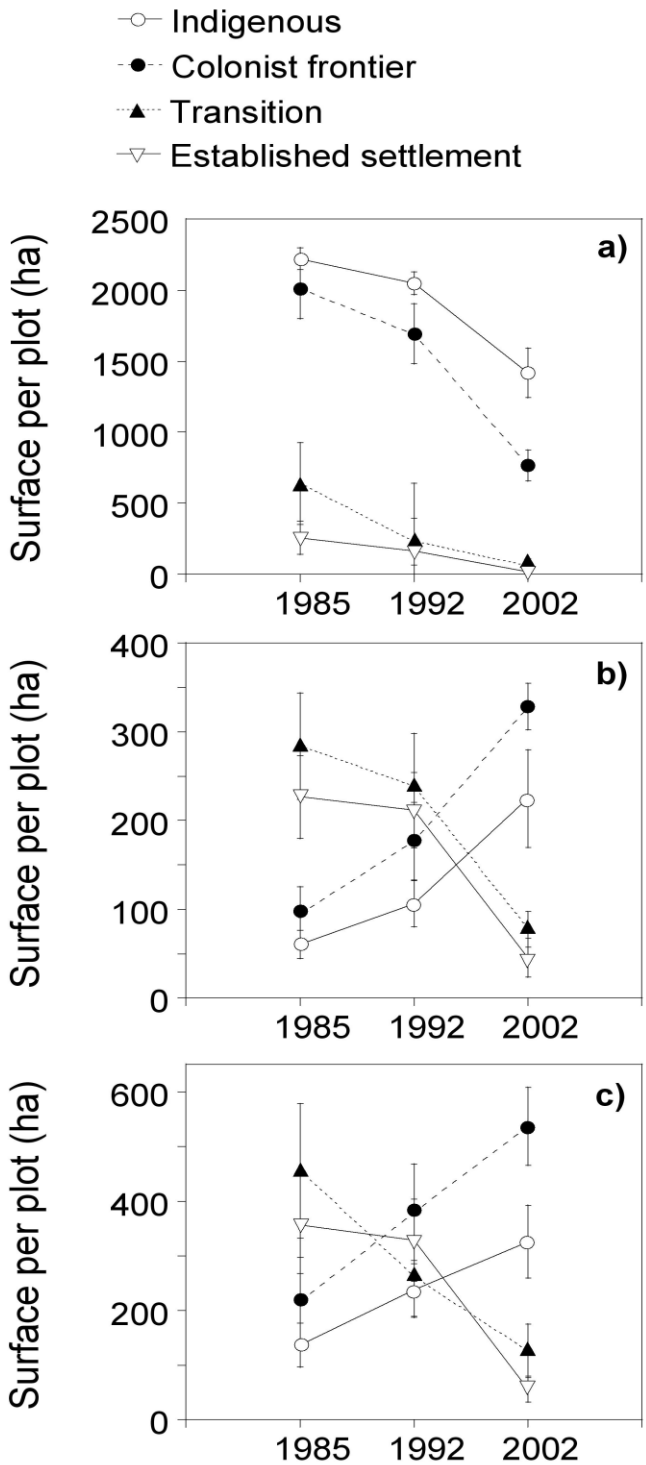

Figure 3.2 Mean (±SE) values of the three fragmentation categories: (a) interior, (b) edge and (c) perforated, for the four human occupation models identified in the Guyana region in the three studied years (1985, 1992 and 2002). N=7 in all cases.

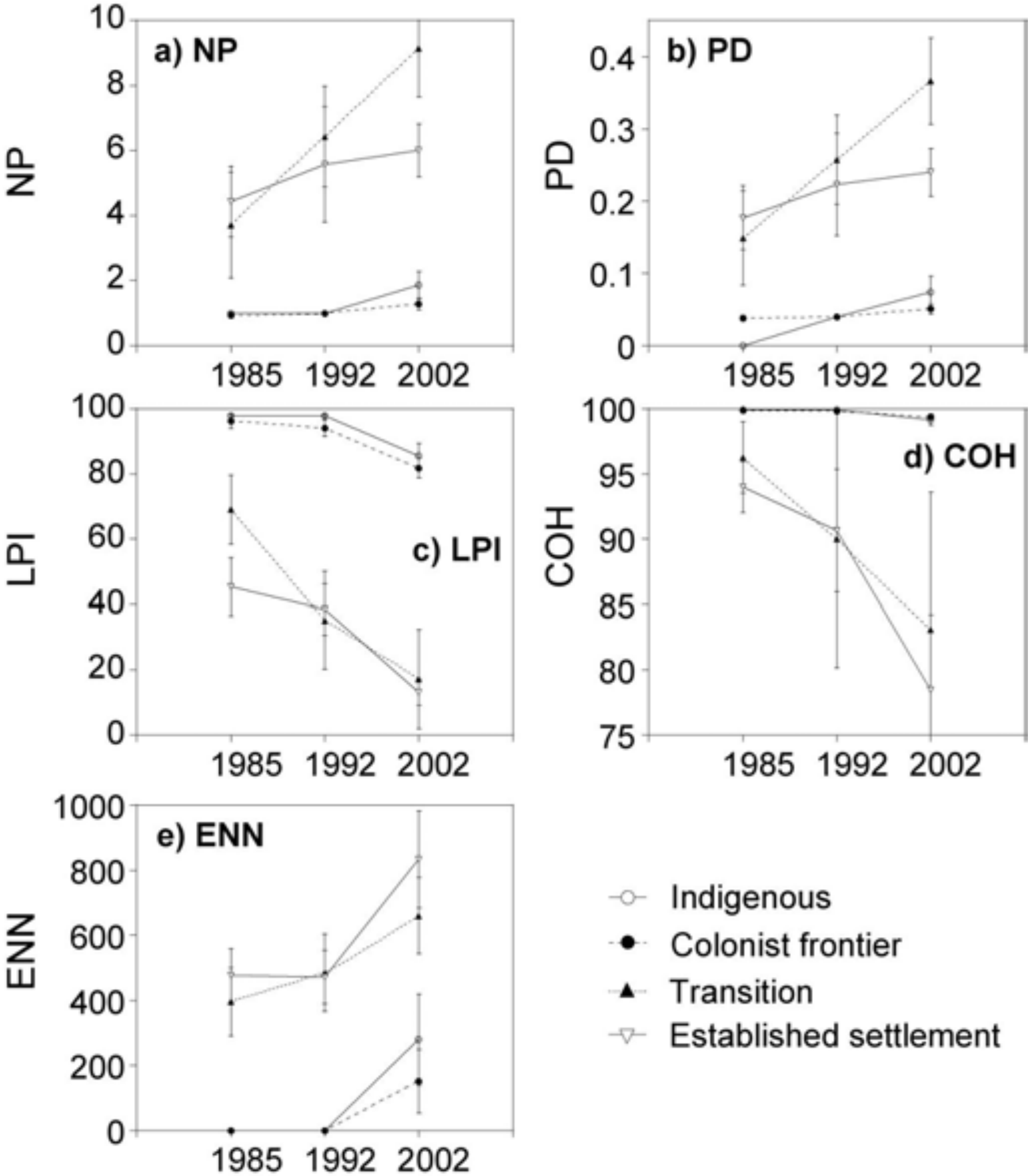

Figure 3.3 Mean (±SE) values of the five fragmentation metrics: (a) NP, (b) DP, (c) LPI, (d) ENN and (e) COH for the four human occupation models identified in the Guyana region in the three studied years (1985, 1992 and 2002). N=7 in all cases.

From our evaluation of decadal forest change as a function of time and categorical distance to rivers, roads and previously deforested pixels, in the case of the indigenous and colonist frontier occupation models, the simulation predicts that forest loss will be more pronounced near rivers, roads and previously deforested areas. This can also be seen in the established settlement and transition areas, which show a rapid drop in deforestation probability at all distances. Remarkably, forest loss at distances shorter than 500m reaches a plateau for this last model after 40 yr (curve marked by triangles in Fig. 3.4c), which is due to the complete deforestation of all locations close to rivers (*e.g.,* rivers are surrounded by deforested areas all along their length). After 40 yr, deforestation in this distance category takes place only in forests close to previously deforested areas. Moreover, these two latter models show a more rapid decline in forested area than the other two occupation models. In fact, all simulations show no forested area remaining after 50 yr in the well-established areas, and the probability map shows 100 percent certainty of deforestation.

3.4. DISCUSSION AND CONCLUSIONS

Overall, our results indicated high variability in regional deforestation rates between the occupation models. Moreover, each spatial pattern, in addition to having its own particular geographic location, has unique characteristics. These patterns are similar to those proposed by Mertens & Lambin (1997), and also used by Geist & Lambin (2001), in which the indigenous and colonist frontier models are equivalent to what these authors called a diffuse pattern. Our results, however, indicate that deforestation rates and fragmentation patterns are significantly different from the colonization front to interior forest occupied by indigenous communities. The deforestation rates and pattern for the transition model fit well with the geometric pattern proposed by Mertens & Lambin (1997). Finally, the well-established population with the economic characteristics of the established settlement model fits well with the patchy deforestation pattern proposed by this classification. The highest deforestation rates for the region correspond to the geometric and patchy deforestation patterns (3.7% and 2.0%, respectively). Similar rates have been observed by other authors for the La Macarena region (0.97%, Armenteras *et al.,* 2006), lowland forests of Colombia (1.5%, Etter *et al.,* 2006a), and Colombian-Ecuadorian Amazonia (1.6%, Viña *et al.,* 2004; 0.9%, Sierra 2000).

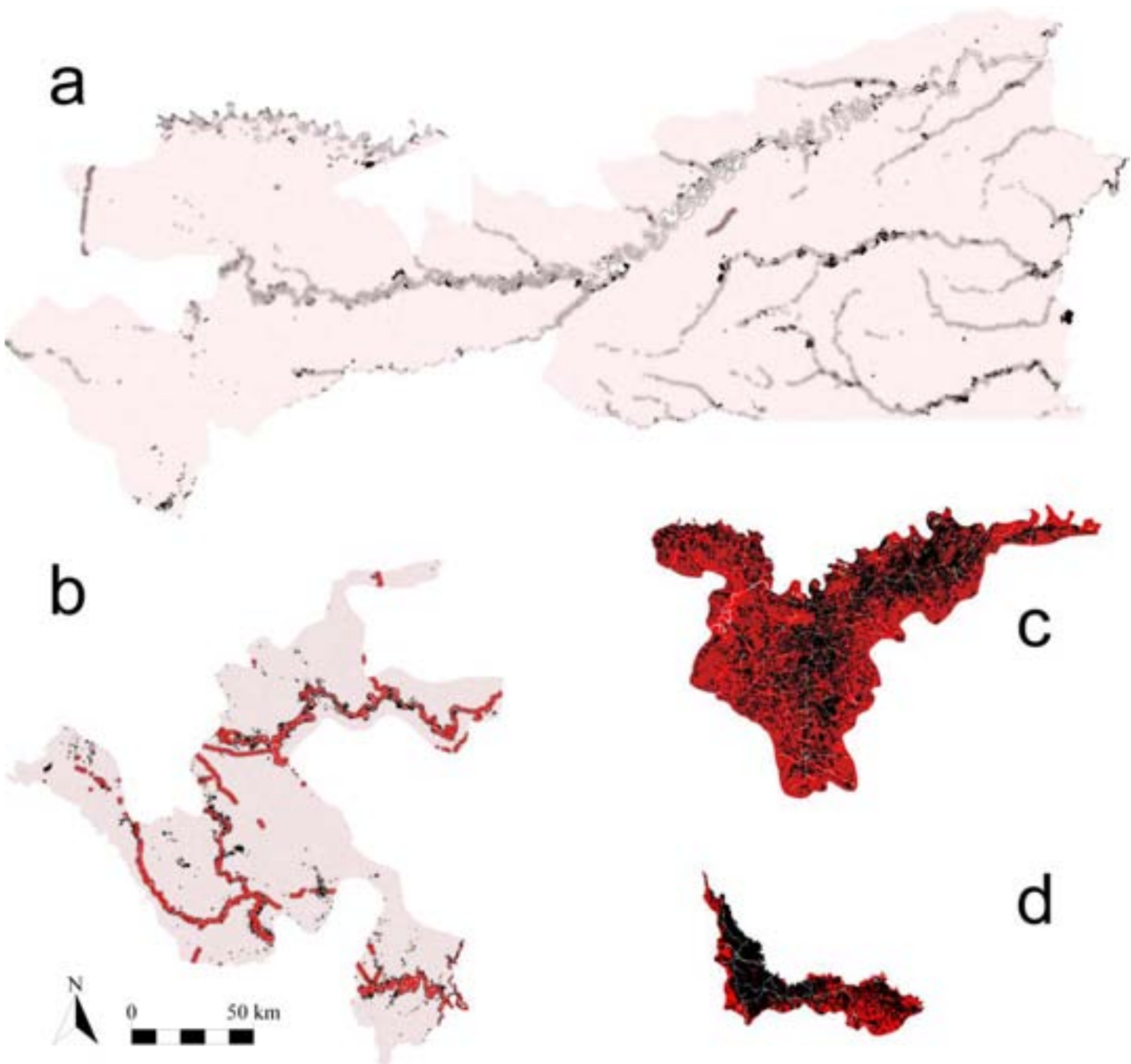

Figure 3.4 Probability maps of pixel deforestation across a 50-year period. Lighter shades of red denote low probabilities, whereas darker shades of red indicate high probabilities of deforestation. Black pixels designate areas that were already deforested in 2002, whereas rivers, roads and areas outside the map limits are shown in white. The four maps correspond to the four human occupation models described in the text: a) indigenous, b) colonist frontier, c) transition and d) established settlement.

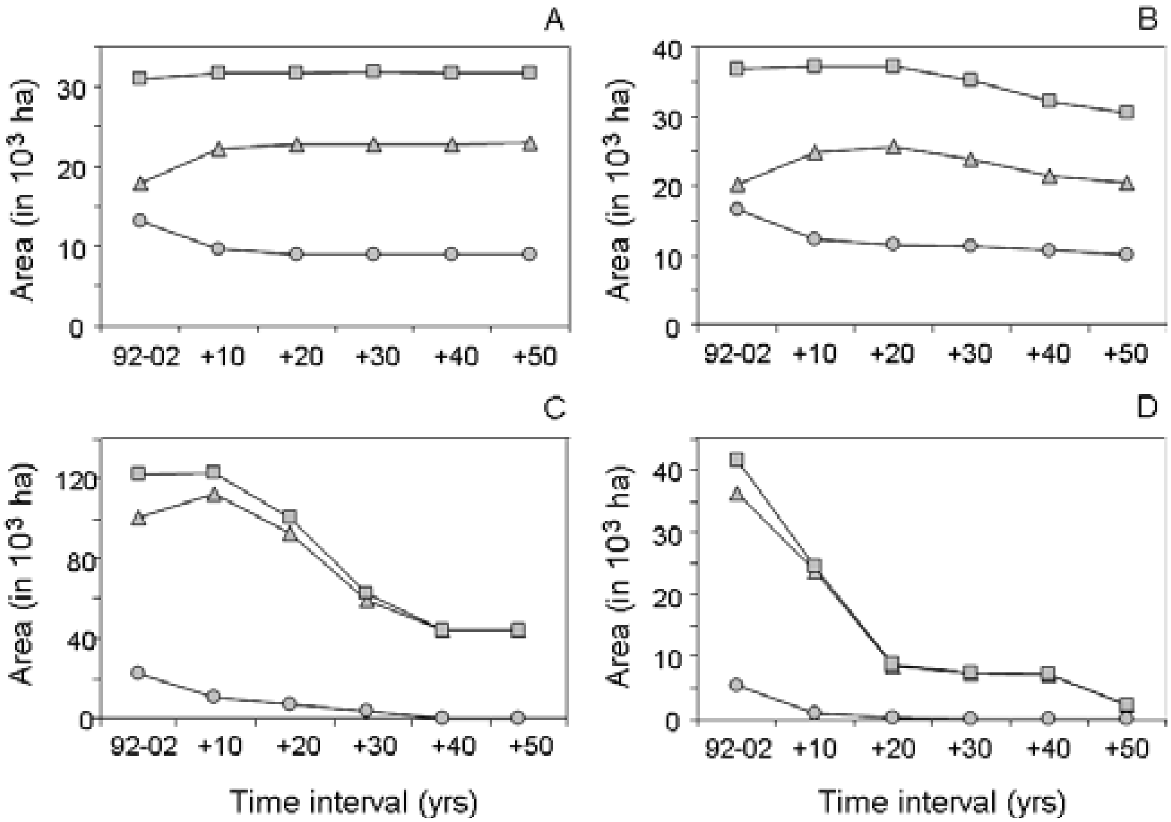

Figure 3.5. Average number of deforested pixels as a function of time and of distance to rivers, roads and previously deforested pixels. Bullets denote areas that are more than two pixels away from rivers, roads and deforested areas, whereas triangles indicate areas at shorter distances and squares show results for all distances. The four figures correspond to the following human occupations models: a) indigenous, b) colonist frontier, c) colonist transition and d) established settlement.

One factor that may affect deforestation rates is related to the dominant landscape matrix found in each pattern, and to the proximity of a patch to a colonization front which may act as an attractor of deforestation. In diffuse patterns, the spatial arrangement is less obvious, and river access plays an important role, especially in areas occupied by indigenous populations who typically established small cultivated parcels ('chagras') in floodplains for subsistence activities. Such activities will arguably not modify the diffuse spatial pattern that we observe in future years. These areas, primarily within indigenous reserves and National Natural Reserves, are buffers against deforestation, as indicated by

Armenteras *et al.,* (2009) (deforestation rates were between 3.98 and 1.49 times higher outside the borders of reserves areas than inside them).

In the colonist frontier model, characterized by a slow and dispersed increase in the number of small parcels, deforestation along rivers and roads is evident, and attractors of deforestation are associated with the opening of new colonization fronts. Geographical data of the System for Illicit Crops Monitoring project for the period from 2000 to 2008 indicate that the progress of coca crops is associated with the transition and established settlement models; thus, coca becomes an important driver of deforestation in the region.

In the patchy and geometric patterns associated with the established settlement and the transition models, respectively, the short distance between transformed patches can lead to accelerated changes. Gutiérrez *et al.,* (2004) have shown that urban centers in the Colombian Amazon play a central role given their location in transitional zones between consolidated colonies and colonization fronts. Furthermore, Etter *et al.,* (2006a) found that accessibility (roads, urban centers and rivers) were the important variables in shaping deforestation in the region. In addition, in these patterns, deforestation tends to be explained primarily by a high spatial autocorrelation coefficient (Aguiar *et al.,* 2007). The geometric pattern shows the greatest variability during this study and has undergone the greatest changes in spatial configuration. This pattern is the result of the important front of consolidation of human colonization along the road between San Jose de Guaviare and Calamar, an axis for access to these settlements. The established settlement area constitutes a strategic zone, given that it directly connects the markets of Villavicencio and San José del Guaviare (Fig. 3.1), where most of the population growth and economic activity occurs along the road axis. In this area, consolidation of the colonization front is evident. Existing protected areas (in particular, the national protected area of the Macarena) have become important barriers to deforestation and fragmentation (Armenteras *et al.,* 2009), which has also been described by Aguiar *et al.,* (2007) in Brazil.

The association of fragmentation patterns with rates of deforestation shows that annual rate of deforestation > 4 percent are found in patterns with < 50 percent interior forest and > 45 percent perforated forest. This result indicates that the patchy and geometric patterns have higher fragmentation indices with an increased forest edge. These data agree with the results of Barbosa & Metzger, (2006) in Brazilian Amazonia forests, who reported a decrease in the survival of interior forest species in areas with a Pf value of < 0.6 of forest and greater fragmentation and decreased connectivity at intermediate values of Pf. In the Colombian Amazonia, Etter *et al.,* (2006b) have also shown that connectivity is lost more quickly at intermediate levels of deforestation and that this relates to the exposed forest edge.

Differences between the occupation models were significant in almost all of the categories and indices of fragmentation analyzed. Relatively small differences are evident in the structure and spatial composition through time in the indigenous model, which may be related to the fact that indigenous communities typically utilize floodplains to establish small cultivated parcels. For the colonist frontier model, occupation is consolidated along rivers (Itilla, Unilla and In´ırida), with a considerable increase of human-transformed fragments (generally illicit crops) within a dominant matrix of forests. As suggested by Arcila *et al.,* (1999), this zone is characterized by a slow, dispersed increase in the number of small parcels in initial stages of deforestation, with a form of linear establishment following the courses of rivers and their effluents with small nuclei whose populations are of migratory origin.

Given the intraregional variability in patterns and trends in the Colombian Guyana, future policies should take these factors into consideration in view of the results obtained with transition and established settlement models. The geometric and patch patterns observed, in which the interior forest category comprises < 30 percent of the total area and the connectivity between fragments declines considerably, must be viewed under the perspective of better connectivity management and secondary ecosystem conservation alternatives. It is necessary to use subpattern divisions and to analyze the underlying drivers that generate these divisions to predict future deforestation patterns and effects for species diversity (as suggested by Ewers & Laurance, 2006).

Throughout the simulations we have assumed that deforestation rates, as measured from the 1992 to 2002 period, will remain constant during the next 50 yr. Even though relevant land cover change drivers may (and some of them certainly will) change in future years, the use of the 1992–2002 rates as representative for the 2002–2052 time period will provide an approximate (and, indeed, useful) idea of what to expect in terms of average patterns of deforestation in the Colombian Amazon.

The annual deforestation rate (0.25%) found in this study indicates that this region has low deforestation rates compared with the rest of South America. The question remains whether the present regional pattern (*i.e.,* forest loss concentrated in just one or two regions while the remaining forest is conserved) is preferable to the alternative (*i.e.,* forest loss spread more homogeneously throughout all regions but not intensively in one particular region). Our results reveal the importance of incorporating spatial pattern projections into the strategic planning of the region, taking into account settlement characteristics. For example, in patterns that show high risks of deforestation and fragmentation through time, incentives and strategies should be oriented toward intensifying land use in the most productive regions and thereby reducing deforestation pressure elsewhere. For this reason, future plans for the region should include clear directives for social investment and deforestation reduction while promoting the use of more technological and wellcapitalized agricultural enterprise. Approaches used to reduce deforestation will also need to be tailored to specific types of land occupation and land uses. In particular, reduced emissions from deforestation and degradation, or payments for environmental services, are alternatives that are being applied in South America, to provide incentives to colonists to maintain ecological processes in the region (Butler & Laurance, 2008; Morse *et al.,* 2009). For low population areas, conservation and sustainable use should be priorities, and planning schemes should avoid providing incentives for the development of enterprise-driven agricultural or large cattle ranching schemes.

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CHAPTER 4

ARE CONSERVATION STRATEGIES EFFECTIVE IN AVOIDING THE DEFORESTATION OF THE COLOMBIAN GUYANA SHIELD?

Armenteras, D., Rodríguez, N. and J. Retana. (2009). Are conservation strategies effective in avoiding the deforestation of the Colombian Guyana Shield? *Biol. Conserv*. 142: 1411-1419.

4. ARE CONSERVATION STRATEGIES EFFECTIVE IN AVOIDING THE DEFORESTATION OF THE COLOMBIAN GUYANA SHIELD?

ABSTRACT

There is general agreement regarding the importance of analysing the territories' roles under different biodiversity management figures in order to support better decision making in the management of natural resources in tropical countries. In this study we analyse the deforestation process to address the question of whether existing strategies such as national protected areas (PAs) and indigenous reservations (IRs) are effective protecting forests in the Colombian Guyana shield. We analyse whether these territories have successfully halted deforestation and agricultural frontier expansion by comparing deforestation occurring within these areas with their surroundings from 1985 to 2002. We also evaluate the impact of roads, illicit crops, and the size of PAs and IRs on deforestation rates. The results indicate that deforestation levels along the outside borders of both management figures were almost four times higher than inside declared PAs and 1.5 times higher than in IRs. However, within IRs, the loss of forested ecosystems was approximately six times greater than inside national parks. As a whole, roads were a significant factor associated with the changes in the region, as well as the influential expansion of coca cultivation particularly outside the national parks. The size of the PAs and indigenous lands also determined their positive impact as barrier against deforestation. Our results suggest strong pressure on areas surrounding PAs, driven by economic forces such as illegal crop expansion, particularly in the last decade. Indigenous lands with small territories have suffered intensive deforestation processes since the 1980s, but changes have been less dramatic in larger areas. Today, PAs are an effective barrier to deforestation, especially given their large extension, but are still under high risk. Future management plans should consider a designed infrastructure development paired with the establishment of new indigenous reservations with minimum viable sizes in order to control accessibility, natural resources extraction, and deforestation.

Keywords: deforestation; Indigenous territories, National Parks, conservation, Guyana Shield

4.1. INTRODUCTION

The conversion and degradation of forest threaten the integrity of forested ecosystems worldwide (Nepstad *et al.,* 1999; Gascon *et al.,* 2000; Achard *et al.,* 2002). In particular, tropical forests play an important role in preserving many ecosystem services and are the primary focus of many conservation efforts, because they contain some of the most species-rich and highly threatened habitats in the world (Myers *et al.,* 2000). Deforestation patterns vary across regions. South America is one of the planet's regions containing larger blocks of forests, with most forest area per capita and fewer fragmented forests, partly as a result of their inaccessible (and thus unexploitable) locations (Rudel, 2006). Indeed, roads and other agents of change such as small-scale farmers, shifting cultivators or population growth have traditionally been associated with tropical deforestation (Rudel, 2006; Butler & Laurance, 2008). Today a shift away from deforestation towards a more industrially driven process is beginning to appear in some regions (Rudel, 2007; Butler & Laurance, 2008). The increasingly deforested frontiers of tropical forests and agricultural expansion has resulted in more focused attention on the best approaches for conservation and management of protected areas, as well as the development of other strategies for biodiversity conservation, such as the role of indigenous reserves (Foster *et al.,* 1999; Du Toit *et al.,* 2004; Román-Cuesta & Martínez-Vilalta, 2006; Nepstad *et al.,* 2006; Oliveira *et al.,* 2007). These areas are central to conservation strategies because they are designed to safeguard remaining habitats and species (DeFries *et al.,* 2005; Joppa *et al.,* 2008). However, when feasible, conservation efforts have tended to focus on the creation of new areas in remote or low density populated areas (Rudel, 2006).

Evaluating the effectiveness of PAs is difficult, especially given the limited data on ecological and social conditions and their changes over time (Naughton-Treves *et al.,* 2005). Measurements of effective long-term protection of biodiversity in PAs have usually been proposed under broad terms (Hockings *et al.,* 2000). Some studies have even developed a methodology to quantify this effectiveness by using questionnaires on aspects related to human pressure and management activities (Bruner *et al.,* 2001). These assessments give a general picture of the conservation and management of tropical biodiversity (Bruner *et al.,* 2001; Rodrigues *et al.,* 2004; DeFries *et al.,* 2005), often revealing threats to national parks caused by clearing, hunting and logging, however, the assessments also generally show these problems to be less severe inside parks than in surroundings (Bruner *et al.,* 2001; Naughton-Treves *et al.,* 2005). It should be noted, however, that these kind of global assessments are often driven by data availability or ease of data collection on a regional or global scale, meaning that there are areas of the world which remain understudied.

The Amazon basin, the Brazilian portion, in particular, contains the world's highest absolute rate of deforestation (Laurance *et al.,* 2001), and has been a primary focus in debates between conservation and development, as well as the effectiveness of conservation units in the whole watershed (Cardille & Foley, 2003; Chomitz & Thomas, 2003; Fearnside, 2005; Joppa *et al.,* 2008). It is also one of the regions where large industrially driven deforestation trends are observed either by agriculture, ranching or oil and gas development (Butler & Laurance, 2008). In contrast, the Guyana shield – another large area of tropical forest wilderness in South America – has the lowest deforestation rate in the world, with almost 90% of its territory in a pristine state (Ter Steege *et al.,* 2000). While there is still no presence of major industrial logging, mining, or agricultural activities in the Guyana shield, the area still faces increasing threats, such as colonisation or increased mining activities (Ter Steege *et al.,* 2000). Little attention has been paid to the extent and drivers of deforestation in this region, especially inside and beyond the boundaries of conservation units, there has also been little attention paid to the role of illicit crops and the presence of indigenous populations with a long-time presence in the region. This lack of information is particularly evident at the Colombian national level. Colombia currently houses nearly 49,000,000 ha of tropical lowland, montane and dry forests (Etter, 1998), 80% of which is nominally protected in natural parks and indigenous or forest reservations (Ponce, 1999). These forests are conservation priorities because they are the last repositories of a highly diverse and endemic biota (Myers *et al.,* 2000). However, despite previous government attempts to manage colonisation processes, rapid deforestation remains virtually uncontrolled (Armenteras *et al.,* 2006; Etter *et al.,* 2005, 2006). In tropical lowlands this is mainly due to traditional drivers such as high colonisation pressures and the intensification of illegal coca (Erythroxylum coca) crops (Viña *et al.,* 2004). Despite future government development plans that include largescale agriculture and oil and gas development that might lead to similar trends occurring in the continent´s other tropical forests (Soares-Filho *et al.,* 2006; Butler & Laurance, 2008), the region still remains under a traditional shifting agriculture, cattle ranching and low population densities – factors that favour the cultivation of illegal crops in marginal lands, decreased accessibility, little institutional presence or law enforcement, and the occasional presence of illegal or armed groups (Armenteras *et al.,* 2006).

This study builds on previous studies that have analysed satellite imagery of deforestation in and around wilderness PAs (Nepstad *et al.,* 2006; Joppa *et al.,* 2008) and further explores issues of addressing deforestation in areas through the inclusion of a previously unanalysed area, and the consideration of significant but little studied issues, such as illegal crop production and the presence of indigenous reserves in the Guyana shield. In this study we also analyse how effective protected areas and indigenous territories have been at mitigating deforestation within their boundaries, as compared with their adjacent buffers (defined as concentric areas surrounding the boundaries of the protected area, whose final area equals the total land of each protected area; see Román-Cuesta & Martínez-Vilalta, 2006) throughout the Colombian Guyana shield. We use a GIS database and satellite data, we examine the extent of existing natural forests, as well as deforestation rates for 1985, 1992 and 2002 within and surrounding PAs and indigenous reservations. Some conservation scientists are increasingly convinced that indigenous residents are necessary actors for the longterm conservation of tropical forests (Schwartzman *et al.,* 2000; Schwartzman & Zimmerman, 2005; Nepstad *et al.,* 2006), and that traditional forest management practices of these indigenous populations can eventually help maintain the natural and cultural values of a region. Thus, we compare the effectiveness of uninhabited (national parks) and inhabited (national indigenous reservations and indigenous reservations) protected territories to mitigate the expansion of the agricultural frontier. Several authors have noted the relationship between site accessibility to markets (through roads or rivers) and the presence of deforestation in lowland tropical forests (Barros Ferraz *et al.,* 2005; Kirby *et al.,* 2006; Mas, 2005; Oliveira *et al.,* 2007). Infrastructures favour land occupation and, illegal activities (such as coca growing), and thus support legal or illegal resource extraction, access to markets, degradation of forests and the fragmentation and deforestation of natural forests. As mentioned, illegal activities in Colombia – especially in remote areas – are also related to armed conflicts and population displacement (Davalos, 2001; Etter *et al.,* 2005), which indirectly affect the expansion of the agricultural frontier, in some cases, land abandonment resulting from these activities cause an increase in secondary and transformed ecosystems, which is highly disturbing to tropical forests. In this study, we evaluate whether management and conservation areas in the Colombian Guyana shield have fewer changes in land cover than unprotected neighbouring areas in the region, we also analyse the role of other driving factors, such as reservation size, roads and the presence of illegal crops.

4.2. MATERIALS AND METHODS

STUDY AREA

Colombia, the fourth largest country in South America, has a population of nearly 1.4 million and is home to some 84 different ethnic groups (Dane, 2005 Census). These ethnic groups make up 3.3% of the country's total population. They are primarily located in rural areas spanning 718 different indigenous reservations. Colombia is considered one of the world's richest countries in terms of both biological and cultural diversity. The National Natural Parks System consists of 53 natural areas, covering about 10% of the national territory.

Figure 4.1 Map locating the national protected areas and indigenous reservations studied in the Colombian Guyana Shield.

The Guyana shield region in South America covers approximately 2.5 million km^2 (Figure 4.1). This region generally bordered in the south by the Amazon River, the Japurá-Caquetá river in the southwest, the Sierra of Macarena and Chiribiquete in the west, the Orinoco and Guaviare rivers in the north and northwest, and the Atlantic Ocean in the east (GSI, 2002). Vegetation types found in the region include sandstone Tepuis (or Table Mountains), white sand vegetation, large savannah areas, coastal swamp forests; gallery forests, and several tropical rain forest systems. The Colombia Guyana Shield, situated between the Amazon and Orinoco basins, is a territory stretching over 200,000 km2 and belongs to the Guyana Western province of the Guyana phytogeographic region (Huber, 1994; Berry *et al.,* 1995). It is comprised mainly of rocky outcrops, sierras and isolated mountains (with a maximum altitude of 1500 m) and has a climate ranging from dry to hot, tropical and humid. Due to its location, the region is high in biodiversity and endemism, but human pressures have progressively expanded agricultural frontiers to the area. Economic activities in the region are mainly related to the extraction of natural resources, followed by the establishment of pastures and crops. Despite (or because of) the lack of proper infrastructure and difficult physical access, illegal crops (mainly coca) are widely present in the region. Nearly 22% of the recorded coca crops in 2004 were located in our study area (UNODC, 2006). According to national census data, the region's total non-indigenous population is 166,230 (Sisben, 2003–2004), 55% of which are located in towns and small settlements and 45% of which are located in rural areas. The indigenous census officially reports a population of 32,764 (Arango & Sánchez, 2004), 58% of which live in the Tuparro National Park area, followed by 30% in the Puinawai area. Of the ethnicities of the indigenous peoples within the studied area, 8% are Nukak and 4% are Chiribiquete. The Macarena area currently does not have any registered indigenous reservations (Rodríguez *et al.,* 2006).

The study area includes five watersheds of the northern region of the northern Colombian Amazon region (La Primavera, Duda, Alto and Bajo Inirida and Mesay), comprising a total area of 12,611,760 ha. This area contains three national parks (Sierra de la Macarena, Serranía de Chiribiquete and Tuparro), two national natural reservations (Nukak and Puinawai) and 44 indigenous reservations (Appendix 1). The most representative biomes of the study area are the tropical forests of Amazonia and Orinoco and the pedobiomes (areas with extreme soil types and azonal vegetation; Walter, 2002) of the humid tropical Amazonia and Orinoquia zonobiome. Natural ecosystems cover a total area of 11,728 936 ha (93.2% of the total area). The areas of greatest transformation are the Nukak and Macarena areas which account for another 882,823 ha (6.8% of the area). The Tuparro and Chiribiquete areas contain the greatest coverage of remaining natural ecosystem, accounting for more than 97% of their catchment area, while the Macarena region has the lowest percentage of natural ecosystems (84%). In general, natural ecosystems have transformed into pastures and a pasture–crop matrix in the Nukak and Macarena areas. The other regions contain an assortment of small traditional crops (e.g. small-scale agriculture as practiced by the indigenous population, known locally as ‘‘chagras”).

METHODOLOGY

Geographic information was collected from LANDSAT TM and ETM satellite images (Rodríguez *et al.,* 2006). We carried out digital classifications to identify land cover changes between 1985 and 2002 at a spatial resolution of 30 m. We selected three time periods for the analysis – 80–90s represented by the years 1985–1992; 90– 00s, represented by the years 1992–2002, and 80–00s, represented by the years 1985–2002. Land cover classification was undertaken using ERDAS Imagine V8.7 (Leica Geosystems, 2005). The Error Matrix, Accuracy Totals, and Kappa Statistics were used to gauge the accuracy of the classification and protocols similar to those used by Meidinger (2003) were used to evaluate the quality of the map classification (employing field work and aerial photography). The final map presented an overall accuracy of 95% for polygons bigger than 25 ha (Rodríguez *et al.,* 2006). A digital database of the road network with a scale of 1:250.000 was obtained from a previous project (Romero *et al.,* 2004) and was updated with the aforementioned satellite image digital processing.

Using this data, we built a GIS database and classified land covers into the following categories: (i) natural, including tropical rainforests, gallery forests, tree vegetation and natural savannas with no detected disturbances, (ii) transformed ecosystems, mainly including agricultural systems, crops, pastures and a matrix of some urban and settlement areas, (iii) secondary ecosystems, including secondary forests, secondary vegetation, disturbed forests primarily caused by pasture and agriculturally abandoned lands (as a transition state between the first two categories) and disturbed forests caused by logging or similar activities (Etter *et al.,* 2005), (iv) rivers; and (v) roads. Information regarding illicit crops in the region was obtained from the global illicit crop monitoring program of the United Nations Office on Drugs and Crime (UNODC, 2006), represented in Colombia by the Integrated System for Illicit Crops Monitoring project or SIMCI (*Sistema Integral de Monitoreo de Cultivos Illicitos*). This system has consistently monitored illicit crops in the region since 2000 and has provided access to coca survey data for the study area. We use the GIS package ArcGIS (ESRI) to conduct all digital spatial analysis.

To compare land cover changes inside and along the national Pas or indigenous reservations, we derived 10 km buffer zones around their perimeters. The size of this 10 km buffer around the areas was chosen to allow comparison with other effectiveness studies (Bruner *et al.,* 2001; Sánchez-Azofeifa *et al.,* 2003; Román-Cuesta & Martínez-Vilalta, 2006) and also because this particular distance provides similar environmental conditions, avoiding heterogeneity in spatial variables that could otherwise bias the assessment (Mas, 2005). For the analysis we excluded reservations with small areas inside the study area (<5000 ha) and also grouped adjacent reservations (creating contiguous indigenous areas), thus avoiding superimposed buffers for those territories. Based on these criteria, we were able to quantify change rates for five PAs, and 14 indigenous territories, representing a total of 8,196,028 ha under some type of conservation management. We also created a 10 km road buffer dataset, and calculated the loss of natural ecosystems within this buffer area.Wethen overlaid this layer with the PAs layer to determining the percentage of area loss around roads which occurred inside PAs, as a way to control and relate it to accessibility.

We used the term “deforestation” to refer to losses of natural ecosystems. Change rates were calculated using R (as in Fearnside,1993), but rates were standardised by the total analysed area in order to avoid undetermined values due to zeros, especially in secondary and transformed ecosystems to which R was also applied. The formula applied used R as $R= (A_1-A_2)/ (A_{ta}*(t_2-t_1))$ where A_1 and A_2 were the areas in hectares at years 1 and 2 respectively (e.g., if looking at the period 1985-1992, A_1 and A_2 were the forest covers in 1985 and 1992, respectively), A_{ta} was the total area analysed for that specific reservation, and t was time in years.

We used non-parametric statistics because most variables were not normally distributed. We first applied Wilcoxon matched paired tests to compare change rates inside and outside buffer areas for both national parks and indigenous reservations. We also performed the Mann Whitney test to compare PAs and indigenous reservations. Using Spearman correlations, we analysed the relationship between ecosystem change rates and the following explanatory variables: length of roads, area of illicit crops, and the size of the management area (another factor that may have implications in future conservation design). These explanatory variables were not highly correlated between them: the only significant correlation was in the elements of illicit crops area and road length s ($R^2 = 0.22$, $p = 0.0016$). Given the low number of samples, all significance tests were carried out at the $p = 0.10$ level. We used SPSS software for all statistical analysis.

4.3. RESULTS

DEFORESTATION

Natural ecosystems still dominate the entire study area, but there was nonetheless an annual average deforestation rate of 0.16% over the period analysed. Regionally, our results indicate that the loss of natural ecosystems in absolute numbers throughout the 17 years was subtle in the studied area (419,243 ha) in comparison to other global tropical regions, but our results also confirm changes in South America were more evident in areas around indigenous reservations and PAs rather than inside these areas. Both protected areas (45,739 ha) and indigenous reservations (35,891 ha) have lost less than 1% of natural forests present in the 80s, while their buffer areas follow a pattern of 5–7% loss (Figure 4.2). Inside national parks, the following natural ecosystems were reduced: Macarena by 17 936 ha; Puinawai by 9715 ha; Nukak by 8727 ha; Tuparro by 5774 ha; and Chiribiquete by 3584 ha. These results represent a small percentage of total deforestation (10% for protected areas, 8% for indigenous reserves) occurring in the region. Mean deforestation rate results for indigenous reservations were 5.8 times higher than those in national protected areas. Despite these results, only a few significant differences in deforestation were found between these two management figures for the 90s–00s period (Table 4.1).

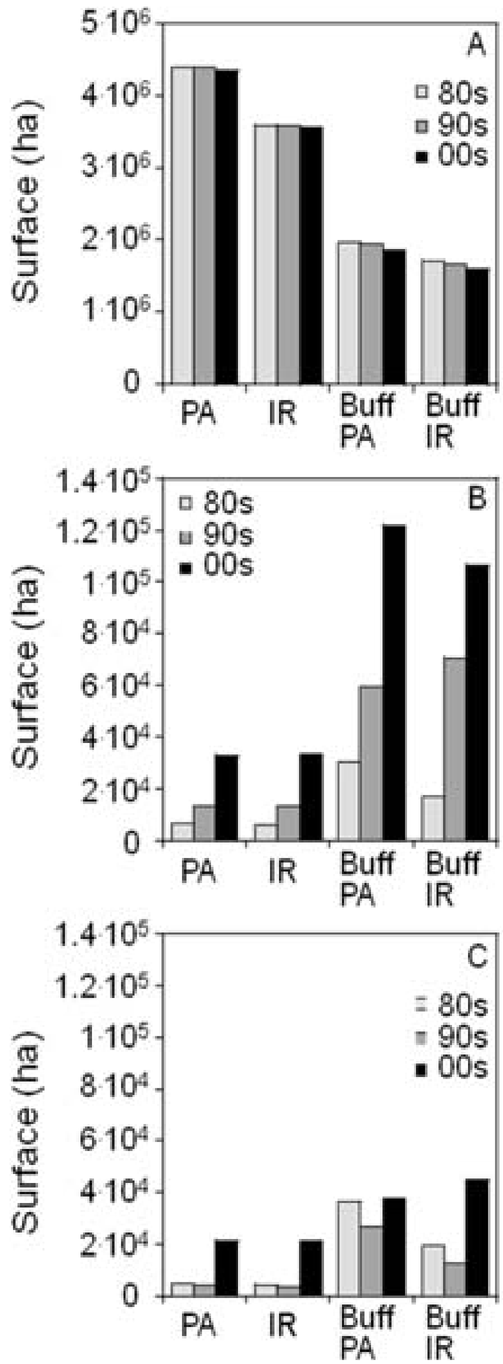

Figure 4.2 Hectares of A) natural, B) transformed and B) secondary ecosystems in national protected areas and indigenous reservations and their buffers in the ‘80s, ‘90s and ‘00s. Note the different scale used in the y-axis of the three graphs. PA, protected area; IR, indigenous reserve; Buff PA, buffer of protected area; Buff IR, buffer of indigenous reserve

On the other hand, significant differences in deforestation rates were found inside national PAs versus their buffer areas (Table 4.1), with relatively higher deforestation rates outside PAs in the 90–00s decade than in the 80–90s decade. On average, deforestation from the 80–00s was 3.98 times higher outside the borders of national PAs (0.28 per year) than inside them (0.071 per year) (Figure 4.3). Deforestation rates were 1.49 times higher outside indigenous reservations than inside them (Figure 4.3), but this difference was only significant for the 80–90s period.

A similar pattern was observed inside and outside PAs and reserves as a result of a more extensive land cover change between secondary and transformed ecosystems. The transformation of ecosystems as a whole increased everywhere (Figure 4.2b), from 6,474 ha to approximately 33,285 ha in PAs and 27,7600 ha more inside indigenous reservations. Expansion in the buffers was at least four times the area that was present in the 80s, with an observed increase of area transformed between 74% and 84% around protected areas and reservations, respectively. The area in secondary forests (Figure 4.2c) was higher in the ‘80s around PAs (36,203 ha) than in indigenous reservations (19,464ha) but the situation reversed in the ‘00s (37,533 ha around national parks in contrast to 44,681 ha in the buffer of indigenous reservations).

The rate of change of transformed ecosystems in the 80s-90s period was significantly higher in the buffer of PAs than inside them, and there was a similar significant increase in transformed ecosystems around indigenous reservations as opposed to the PAs inside them (Table 4.1). As with deforestation rates, the decades of highest change in transformed ecosystems did not coincide for national PAs and indigenous reservations. Secondary ecosystems showed no significant differences among categories of management or among any analysed time period (Table 4.1).

Table 4.1 Results of the non parametric test carried out for the comparison of change rates of the different ecosystem types (NE, natural ecosystems; TE, transformed ecosystems; SE, secondary ecosystems), road length and coca cultures between the two management categories and between each of them and their buffers (PA, protected area; IR, indigenous reservation; Buff PA, buffer of the protected area; Buff IR, buffer of the indigenous reservation) in the three periods considered (80-00, 80-90 and 90-00). Statistical tests: [a]Mann Withney Test, [b]Wilcoxon Matched Pairs Test). Ns, not significant.

Non parametric tests between categories of management	**NE**			**TE**			**SE**			**Roads**	**Coca**
	80-00	80-90	90-00	80-00	80-90	90-00	80-00	80-90	90-00		
PA and IR [a]	ns	ns	Z=2.2 p=0.026	ns	ns	ns	ns	ns	ns	ns	Z=1.9 p=0.058
PA and Buff PA [b]	Z=2.0 p=0.043	ns	Z=2.0 p=0.043	Z=2.0 p=0.043	ns	Z=1.8 p=0.068	ns	ns	ns	Z=1.7 p=0.079	Z=1.8 p=0.06
IR and Buff IR [b]	ns	Z=1.7 p=0.080	ns	Z=2.0 p=0.041	Z=2.0 p=0.046	ns	ns	ns	ns	Z=2.5 p=0.013	ns

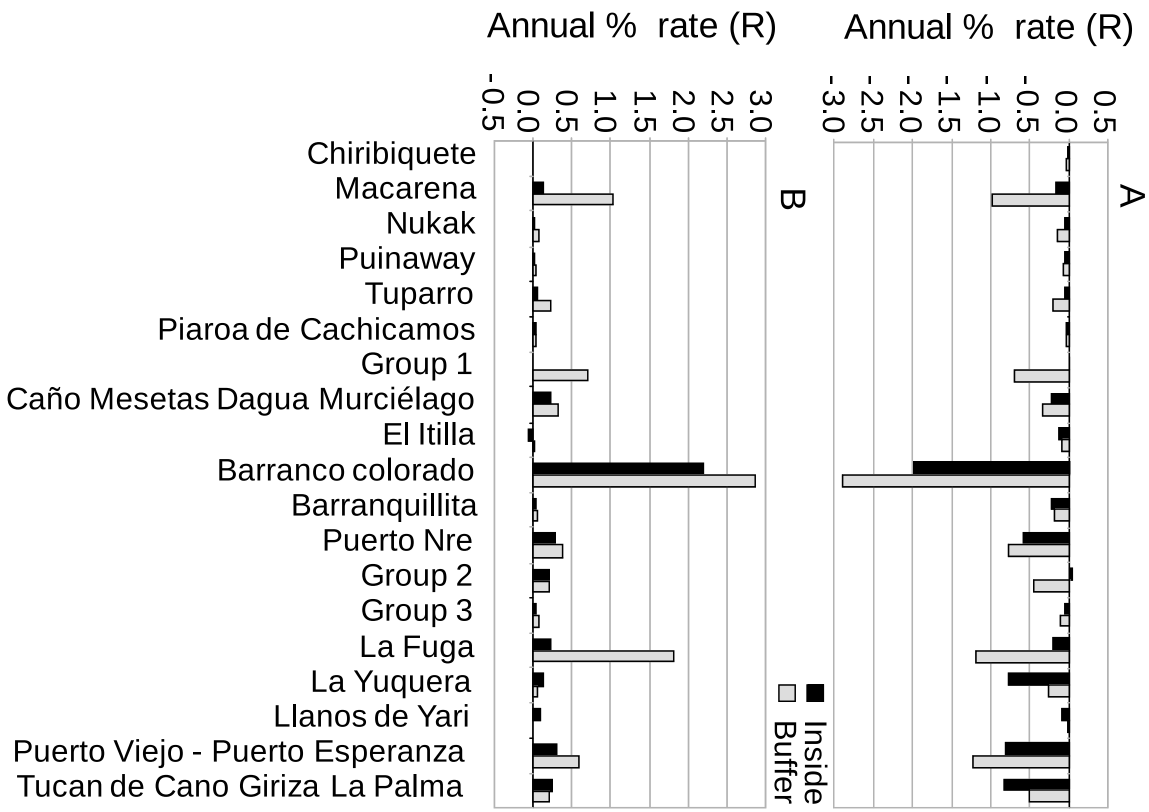

Figure 4.3 Change rate for A) natural ecosystems and B) transformed ecosystems in each national protected area and indigenous reservation (in black) and its buffer (in grey) from 1985 to 2002. PA, protected area; IR, indigenous reserve; Buff PA, buffer of protected area; Buff IR, buffer of indigenous reserve. The indigenous reservations included in groups 1, 2 and 3 are indicated in Appendix 1.

DRIVERS OF CHANGE

The three variables (roads, coca crops and size of the management area), showed significant relationships with the different types of ecosystem management category (Table 4.1). There was no significant difference in the length of roads in PAs compared to indigenous reservations. Road length was significantly greater (by at least three times) in the buffer outside both PAs and indigenous reservations than inside them (Table 4.1). In both cases, when management areas had road infrastructure developments of any kind, the areas were more likely to have forest loss than those without accessibility. Indeed, roads were also a strong factor in land cover changes occurring outside the borders of both management categories, the greater the number of road kilometers, the greater the land cover change figures. The results of the analysis of the 10 km buffer around roads showed that of the total loss of natural ecosystems reported in the study area, 336,347 ha occurred within this buffer (80% of total documented deforestation). Of these losses, only 15,526 ha (representing 3.7% of the total deforested study area) were inside PAs and 5400 ha (1.3% of the total deforested study) were inside indigenous reserves. This means that only 33% of deforestation inside the PAs (45,739 ha) and only 15% of deforestation inside indigenous reserves (35,891 ha) could be explained by accessibility by roads. As expected, most of this activity occured in two areas: the Macarena National Park (12,262 ha) and Tuparro (2305 ha).

In the case of illicit crops, results showed larger areas containing coca crops within indigenous reservations than within national parks (Table 4.1). There was also a significant difference between the hectares of coca grown inside and outside national PAs. Illegal crops were also specifically related to deforestation and land cover changes in the 10 km buffers outside both PAs and indigenous reservations. The difference between indigenous reservations and their buffers carried no substantial significance (Table 4.1), although the area of coca outside reservations was on average 3 times higher than areas inside them. Our results also indicate that during the studied time period, the size of the management area (i.e., a national PA or an indigenous reservation) had a strong negative correlation to deforestation, both inside their limits and along their buffers (Table 4.2); the larger the management area, the lower the loss rate.

Table 4.2 Spearman correlation analyses between change rates of the different ecosystem types (NE, natural ecosystems; TE, transformed ecosystems; SE, secondary ecosystems) and the different factors that can affect them (coca cultivation, roads and area size) for the periods '80-'00 and '90-'00 and the different categories of management (PA, protected area; Buff PA, buffer of the protected area; IR, indigenous reservation; Buff IR, buffer of the indigenous reservation). In each case, the rho value and its significance are indicated. ns, not significant.

	Coca crops						**Roads**						**Area size**					
	NE		**TE**		**SE**		**NE**		**TE**		**SE**		**NE**		**TE**		**SE**	
Category	80-00	90-00	80-0	90-00	80-00	90-00	80-00	90-00	80-00	90-00	80-0	90-0	80-00	90-00	80-00	90-00	80-00	90-00
PA y Buff PA [a]	Ns	0.929 0.001	ns	- 0.905 0.002	Ns	ns	ns	ns	ns	ns	ns	ns	- 0.763 0.010	- 0.927 0.001	0.837 0.003	ns	ns	ns
IR y Buff IR [b]	Ns	ns	ns	ns	0.588 0.001	ns	ns	ns	ns	0.582 0.004	ns	ns	- 0.518 0.005	- 0.460 0.031	ns	ns	ns	ns
Buff PA y Buff IR [c]	Ns	0.646 0.009	ns	ns	0.631 0.004	0.719 0.003	0.668 0.002	0.821 0.000	0.559 0.013	- 0.818 0.000	ns	ns	- 0.472 0.041	ns	ns	ns	ns	ns
PA y IR [c]	ns	ns	ns	0.518 0.048	ns	ns	ns	ns	ns	0.538 0.038	ns	ns	- 0.667 0.002	- 0.768 0.001	0.507 0.027	ns	ns	0.618 0.014

[a] n=10, [b] n=28, [c] n=19

4.4. DISCUSSION AND CONCLUSIONS

In the Colombia Guyana shield, national protected areas have slower deforestation rates and perform better at slowing deforestation rates than indigenous reservations. As concluded in the case of the Peruvian Amazon (Oliveira *et al.,* 2007), our results suggest that both management types can be an effective way of protecting forests. However, legally established national PAs are less likely to be affected by a colonisation wave than indigenous reservations. Despite this fact, protected areas have been under increasingly stronger pressures in their surroundings since the 90s. There are clear differences between the performance of PAs versus that of indigenous reserves, and most of the variability can be explained by the history of colonisation and the area's proximity and accessibility to the Andes. The Andes houses most of the Colombian population and is the origination of the colonisation waves. The general relation between deforestation rates and coca crops for indigenous reservations is strong, especially in the 80s, when armed conflicts related to illegal activities forced widespread land abandonment and directedhuman migration towards small indigenous reservations that had been previously established close to the colonisation front. In the 90s coca fields might have extended to the outskirts of some of the national PAs (Macarena, Nukak and Puinawai), all of which were located near colonisation fronts. In fact, the Macarena National Park (the closest park to the Andes), is the most transformed of the five protected areas in this study, showing higher rates of deforestation, more hectares of coca crops, and more roads. This can be explained by longterm colonist exploitation that has occurred since the 70s (Armenteras *et al.,* 2006). This is mainly related to cattle farming and illegal crops, which stem from weak government policies of the 80s and 90s, which led to the presence of multiple illegal armed groups. No indigenous lands have been designated in the area. Meanwhile, Chiribiquete National Park is found in a highly inaccessible area, is nearly without any transport infrastructure, and has some of the lowest deforestation rates of any national PAs. Puinawai and Nukak follow closely, both are national PAs but are managed by indigenous peoples, and are also difficult to access. Finally, Tuparro National Park, which is close to the Venezuelan border, has the second highest land cover change of all national PAs, despite being highly inaccessible from within Colombian territory. Neither Chiribiquete nor Tuparro have been widely opened to illicit crop expansion. Conversely, Nukak and Puinawai contain the presence of coca crops both inside and in their buffers, though not at the same levels as Macarena. This can be partly explained by Puinawai, but cannot fully account for the indigenous populations' use of coca for traditional purposes. In the case of Nukak, recent facts suggest a forced migration of indigenous population by illicit groups involved in illegal coca traffic.

While Brazilian indigenous lands have been proven to reduce deforestation in active agricultural frontiers in the Amazon (Nepstad *et al.,* 2006), indigenous lands in the Colombian Guyana shield have not been as successful at reducing deforestation as have national PAs. The Colombian indigenous territories play an important role in diminishing deforestation rates within their borders, but our results still suggest that they have high rates of deforestation along their 10 km buffer zones. Most of this deforestation occurred in the 80s with the coca boom and resulting migration of colonists, but there is much variability between individual reservations. These variables can be partly determined by the size of the territories, but are also related to their accessibility and the individual colonisation history of the area. We found significant correlation between deforestation rates and the size of the indigenous reservations, smaller reservations are clearly less able to inhibit deforestation along their borders or even inside them (Figure 4.3). However, some of the 'hotspots' of deforestation in indigenous reservations were located in the Department of Guaviare along the colonised border of San José del Guaviare (a former peace zone). Two of the smallest reservations, Barranco Colorado and La Fuga, are located in a region that is easily accessed, containing the highest density of road kilometers (after the Macarena area). These two reservations are also located on roads built following a wave of forest exploitation by non-indigenous populations, mainly related to cattle farming. The area's recent river transportation network is related to the illegal extraction of resources and the expansion of coca crops. Other deforestation 'hotspots' in or around indigenous lands are found in the same department but along the Miraflores-Barranquillita area south of the previously mentioned colonisation frontier. Miraflores is a municipal level settlement with mostly indigenous inhabitants, which also has a floating population that fluctuates with the economic and productivity cycles of the coca ''boom". As a result, some reservations presented higher deforestation rates inside the reservations than outside, which can be partly explained by the major deforestation that had already occurred outside their limits. On the other hand, the lowest deforestation rates for indigenous lands are present in the reservations around the Tuparro National Park and

Puinawai area, these are coincidently the most inaccessible areas, made up of mostly indigenous populations, with small settlements of colonist families that dedicate themselves to the illegal trafficking of contraband goods across the border. However, due to lack of data, forest resource extraction activities such as legal or illegal logging, poaching or hunting could not be considered in this study.

Transformation of forests lead to an increase in transformed ecosystems in most of the areas analyzed for deforestation. In fact there is a 374,111 ha increase in this type of ecosystem in the whole study area between 80s and 00s, 14.5% of which occurred inside protected areas (26,808 ha) and indigenous reserves (27,760 ha) and 52% around their buffers (91,248 ha and 89,823 ha respectively). This makes sense, since land cover change from forest to other land cover, driven mainly by agricultural activities, damages forest and removes forest cover through the extraction of resources, clear cutting and the establishment of settlements (Etter *et al.,* 2006; Rodriguez *et al.,* 2006). An increase in transformed forests for those ecosystems is also, as expected, related to the road network around reservations and parks. Conversely, our results on secondary ecosystems, as a transition stage between natural and transformed ecosystems, were related more to hectares of coca crops. From the total 148,557 ha of secondary ecosystems that increased since the 80's in the region, 28% of them occurred either inside protected areas or indigenous reserves and 52% in their buffers. This may suggest that there has been an important abandonment of coca fields or migration of crops to other areas that could be due to government eradication programs. However, it seems they may be reducing production but expanding cultivation zones. This is particularly important since secondary ecosystems showed no relation at all to existing roads.

Transformation of forests lead to an increase in transformed ecosystems in most of the areas analysed for deforestation. The increase in this type of ecosystem within the study area between 80s–00s occurred much less intensely inside protected areas and indigenous reserves than around their buffers. This makes sense, since land cover change from forests to other land cover (driven mainly by agricultural activities), damages forests, removing forest cover through the extraction of resources, clear cutting, and the establishment of settlements (Etter *et al.,* 2006; Rodríguez *et al.,* 2006). An increase in transformed forests for these ecosystems is also, as expected, related to the road network around reservations and parks. Conversely, our results on secondary ecosystems (used as a transition stage between natural and transformed ecosystems), were related more to hectares of coca crops. Again, the increase of secondary ecosystems since the 80s in the region occurred preferentially in the buffers of protected areas or indigenous reserves than inside them. This may suggest that there has been an important abandonment of coca fields, or a migration of crops to other areas as a result of government eradication programs. However, it seems they may not be reducing production, but rather expanding cultivation zones. This is particularly important since secondary ecosystems showed no relation at all to existing roads.

Following Joppa *et al.,* (2008)'s classification of de facto versus de jure protection, areas in the Guyana shield probably contain a combination of both protection types. Some areas escape human activity due to physical inaccessibility; others are probably protected (and some only partially, as in cases such as Macarena) because of their legal status. Neither the five protected areas nor most of the reservations are in fact paper parks (Joppa *et al.,* 2008), but some of the indigenous reservations in the area can nonetheless be labelled as such, since they do not provide conservation or sustainable use of forests. Future conservation and development paths (both regional and international), including policies, legislation and land cover planning must consider spatial planning as an important component of successful development. Successful development must balance the economic, cultural, social and environmental aspects of the relatively well-preserved Guyana Shield in Colombia. In agreement with Joppa *et al.,* (2008), the government, its managers and its decision-makers should take into serious consideration, along with biological and cultural criteria, the remoteness and size of future parks and, reservations, and should even consider the expansion of existing management areas to increase their extent.

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DISCUSIÓN GENERAL

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Los capítulos presentados en la tesis muestran los siguientes resultados: (i) existen diferencias regionales e intra-regionales en los procesos y patrones de cambio de cobertura y uso del suelo asociados específicamente con la deforestación; (ii) los atractores de cambio como la accesibilidad y distancia a centros poblados tienen una importante influencia en la probabilidad de deforestación y cambio de uso del suelo independientemente de la región; (iii) los modelos espacialmente explícitos tienen una elevada capacidad de análisis de la dinámica de LUCC en comparación con los modelos lineales generalizados; y (iv) la presencia de áreas protegidas es una figura importante para disminuir el cambio de uso de los paisajes.

Patrones de deforestación

Si bien la deforestación tropical es la principal fuente del cambio de la cobertura del suelo en el mundo, es un proceso diferencial en magnitud, patrones espaciales y fuerzas de cambio que varían entre las regiones y aun en el interior de ellas (Geist *et al.,* 2006). Para Colombia encontramos diferencias en las tasas anuales de deforestación en las regiones de estudio, siendo para Guyana (tierras bajas) de 0.25% y para Andes (tierras altas) de 1.41% (ver Capítulos 1 y 3). No obstante en la región de Guyana se evidenciaron los mayores contrastes en las tasas de deforestación (entre 0.04% y 3.68% en diferentes zonas) y están posiblemente relacionadas con los patrones de ocupación del territorio durante los últimos 70 años. En Andes, pese a tener una historia intensa de cambio de uso del suelo desde el siglo XIX, las diferencias en tasas de deforestación son significativas entre los bosques montanos y de piedemonte (en inglés, lowlands), estando las de estos últimos asociadas a la apertura de nuevas fronteras de colonización hacia la Amazonia a partir de la segunda mitad del siglo XX.

Lo anterior plantea que cada región se halla en diferentes fases de deforestación. Así, Guyana presenta una mayor variabilidad intrarregional debido a que existen fases iniciales de la pérdida de bosques con tasas bajas que van aumentando paulatinamente, fases intermedias caracterizadas por una pérdida rápida de bosques donde la relación bosque/no bosque tiende a ser similar, y una fase final en la que la pérdida de bosques alcanza su máxima tasa y decrece cuando la matriz dominante es transformada. Este patrón es similar al documentado por Etter *et al.,* (2005) para bosques tropicales bajos donde la deforestación sigue un patrón sigmoidal, cuya fase de estabilización contiene bajo porcentaje de bosque. En Andes, podemos identificar para los bosques montanos una fase estable donde los remanentes boscosos han persistido en el tiempo inmersos en una matriz transformada, mientras que en los bosques bajos, se podría pensar en una fase entre inicial e intermedia dependiendo de la ubicación geográfica donde se da el proceso. Al igual que la tasa de deforestación, los índices de fragmentación y el modelo de fragmentación de Riitters reafirman los resultados presentados anteriormente, es decir que la dinámica de los procesos de fragmentación son interdependientes del patrón de deforestación asociado.

Cabe resaltar que algunos resultados de esta tesis (ver Capítulos 2 y 4) se emplearon para identificar las áreas bajo una mayor amenaza de la deforestación (hotspots). Para Guyana, se identificaron dos hotspots, uno a lo largo de la frontera de colonización de San José del Guaviare (patrón geométrico) y el otro en la zona al sur de Miraflores, Barranquillita (patrón difuso colono). Estos hotspots se asocian a algunas reservas indígenas con cercanía a carreteras secundarias. Para Andes se estima que los bosques bajos andinos (lowlands) ubicados en límites entre Andes-Amazonia, Andes-Pacífico y La serranía de San Lucas, así como los bosques montanos de la cordillera oriental, se encuentran bajo una mayor amenaza de conversión. Estas áreas coinciden con las identificadas por Wassenaar *et al.,* (2007) para Suramérica. Las áreas amenazadas probablemente pueden ser más altas en un futuro próximo si hay una intensificación agrícola basada en el aumento del plantaciones de palma de aceite y biocombustibles estimulando, como plantean Rudel *et al.* (2009), la generación de nuevos flujos de comercio internacional y nuevas presiones sobre los bosques.

Factores y escenarios de cambio

Aunque los factores socioeconómicos, demográficos, y biofísicos ayudan a explicar los procesos de deforestación y cambio de uso del suelo, parte de las diferencias entre las fases de deforestación en ambas regiones se relacionan con la accesibilidad a los bosques, influenciada por la presencia de carreteras y cercanía a centros poblados. Para los bosques montanos de los Andes y los bosques asociados a los patrones de deforestación tipo parche y geométrico de Guyana, el desarrollo de infraestructuras de transporte ha influido en la accesibilidad al territorio y esto podría haber llevado a una mayor deforestación en áreas inicialmente con mejores condiciones biofísicas para las actividades agrícolas y pecuarias (pendiente, precipitación, suelos) y en áreas con cercanía a las capitales de departamento o ciudades intermedias que presentan una actividad económica importante (ver Capítulos 1, 2 y 3).

Asimismo, los procesos de deforestación en bosques bajos de Andes y en los bosques del modelo de ocupación colono (patrón difuso) de Guyana están asociados con la ampliación de la frontera de colonización (no planificada) y el crecimiento poblacional generalmente de campesinos/colonos itinerantes y desplazados de las zonas altas de los Andes. Cabe destacar la influencia que tiene la cercanía a áreas con pastos sobre las probabilidades de deforestación, siendo el establecimiento de pasturas una clara señal de la colonización de nuevas áreas y tal vez esta transición a pasturas la que más incide en procesos de cambio de uso del suelo durante el período de estudio (1985 a 2000) y en general en Colombia (Wassenaar *et al.,* 2007).

Los resultados encontrados en esta tesis muestran dos aspectos interesantes en los procesos de deforestación: de una parte se destaca la incidencia de cultivos ilícitos en ambas regiones, pero creemos que en Guyana este factor ha sido uno de los grandes impulsores de cambio desde la década de los 80´s y, a diferencia de los patrones de deforestación tropical presentes en Brasil y algunos sectores de Ecuador (espina de pescado), la presencia de coca en Colombia ha incidido en la configuración espacio-temporal de los patrones de deforestación actuales (difusos y geométricos) en las tierras bajas (Armenteras *et al.,* 2006). Por otro lado, la inestabilidad interna ocurrida en el país en las últimas décadas asociada en nuestro trabajo al desplazamiento forzado de la población, ha traído consecuencias regionales en los patrones de cambio de uso del suelo que incluyen el incremento de vegetación secundaria asociada al abandono de tierras en ciertas áreas de los Andes y la migración hacia las grandes ciudades (Capítulo 1 y 2) y la apertura de nuevos frentes de colonización en tierras bajas de los Andes y en los sectores más cercanos a la cordillera oriental en límites con Amazonia.

Respecto a la identificación de transiciones de uso, los submodelos para Andes fueron satisfactorios y la validación arrojo un coeficiente de Kappa = 0.85. Resultados de las simulaciones sugieren que bajo un escenario de conversión a pastizales se induce la mayor deforestación y que los impactos potenciales sobre la tala de bosques están asicados a los bosques bajos y a bosques montanos de la cordillera Oriental. Para

Guyana la simulación de la deforestación mediante modelos matemáticos mostró para el patrón difuso indígena una probabilidad baja deforestación (0.01), mientras que en los bosques asociados a los patrones difuso colono y geométrico, la probabilidad de deforestación fue de 0.8, estando asociada a los lugares más cercanos a ríos, carreteras o zonas previamente deforestadas.

Los resultados presentados muestran un amplio rango de factores y atractores de cambio que influyen en LUCC. Al hacer una comparación de las variables explicativas incluidas en los modelos lineales generalizados (GLM) y en la Multi- Layer Perceptron (MLP) (Capítulos 1 y 2), se establece que las vías, la precipitación, el tipo y la fertilidad del suelo y la distancia a bosques son los principales impulsores de la deforestación observada en la región andina entre 1985 y 2000, lo cual es consistente con otros estudios (Etter *et al.,* 2006; Orrego, 2009). Sin embargo la importancia de estas variables varía dependiendo del tipo de bosque. Variables como la actividad económica y necesidades básicas insatisfechas no fueron relevantes en MLP pero si en GLM. La resolución de la información utilizada en estos modelos puede haber contribuido a identificar factores tan diferentes y específicamente el hecho de utilizar como unidad de análisis espacial en los GLM el municipio probablemente ocasiono una pérdida de información.

Creemos que los modelos LUCC se pueden utilizar en forma complementaria, ya que esto permite contar con información adicional para comprender mejor la dinámica de cambio. Una ventaja de usar los modelos espacialmente explícitos es que, aparte de explorar las relaciones entre cambio de uso del suelo/deforestación y una serie de variables explicativas, dan pautas para analizar los patrones y dinámicas de cambio en un ámbito espacial donde muchos estudios de patrones o procesos que ocurren al interior de los ecosistemas deben ser explicados por su naturaleza espacial.

Implicaciones para la conservación

Aunque en Colombia, históricamente se hayan promulgado políticas gubernamentales para los procesos de colonización, la deforestación es alta y sigue siendo incontrolada. Algunas políticas como el impulso a la agroindustria en gran escala, exploraciones de gas y competitividad en mercados internacionales pueden llevar a tendencias similares a los de otros bosques tropicales con fuertes implicaciones sobre los ecosistemas. Comprender la dinámica de cambio de la cobertura y uso del suelo es un tema difícil de abordar debido a los múltiples factores y contextos que influyen en ella. Sin embargo, su entendimiento es relevante frente a estrategias de conservación de la biodiversidad, ordenamiento del territorio, manejo de áreas protegidas, y análisis del cambio climático. Tres aspectos son importantes a considerar:

(i) Los estudios futuros deberán contener una mejor base de información, especialmente de variables asociadas de una parte con procesos de cambio tales como tala selectiva, incendios y tasas de regeneración y de otro lado con políticas sectoriales, actividad económica por diferentes sectores, tenencia de la tierra. Esto es con el fin de aplicar modelos combinados de LUCC que pueden ayudar a identificar lineamientos generales de política en relación a la reducción de la presión sobre los bosques y un manejo más integral del recurso suelo.

(ii) De acuerdo con el esquema planteado por Joppa *et al.* (2008) "*de facto versus de jure*", se deberá evaluar la efectividad de las figuras de conservación y su relación con los futuros escenarios de cambio para orientar la inversión en protección y gestión de estas figuras legales.

(iii) Puede pensarse en dar un valor de uso a los servicios que prestan los ecosistemas boscosos y áreas en proceso de regeneración y mediante instrumentos de política como REDD o instrumentos de mercado como el pago por servicios ambientales (PSA). De esa manera se lograrían nuevas oportunidades para la conservación de los bosques tropicales.

Algunos estudios han sugerido la importancia de las poblaciones indígenas y las figuras de protección de orden nacional o local para la conservación a largo plazo de los bosques tropicales (Nepstad *et al.,* 2006; Oliveira *et al.,* 2007). Los resultados obtenidos en el capítulo 4 ponen de manifiesto una fuerte correlación entre la tasa de deforestación y la presencia de áreas protegidas y resguardos indígenas, siendo las áreas protegidas más efectivas frente a la deforestación. Nuestros resultados sugieren una alta presión sobre las áreas de amortiguación alrededor de los Parques Nacionales Naturales, especialmente en la zona andino-amazonense, mientras que en parques inaccesibles generalmente asociados a la Guyana la probabilidad de deforestación es baja. Asimismo, los remanentes de bosques ubicados en sitios con poca accesibilidad (pendiente) de los Andes han persistido en el tiempo y algunas de las áreas boscosas bajo mayor amenaza de conversión están asociadas a zonas cuyos niveles de diversidad son altos y podrían ser considerados como sitios potenciales para ser incluidos en un Sistema Regional de Áreas Protegidas.

Finalmente, siguiendo el planteamiento de Rudel *et al.,* (2009) de acuerdo a los cambios en las agentes de la deforestación, las estrategias plausibles para la conservación de tierras altas (Andes) son el diseño y la puesta en funcionamiento de los sistemas de áreas protegidas regionales que integran una red de reservas conformadas por el sistema de parques nacionales naturales existentes y el incremento de la conectividad en paisajes generalmente ganaderos o bosques secundarios. Para las tierras bajas (Guyana), se deberán implementar acuerdos de gestión entre las comunidades indígenas, colonos y estado con el fin fomentar agroindustrias basadas en productos del bosque.

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Appendix 1. Main characteristics of the national protected areas (PA) and indigenous reservations (IR) analysed in this study including deforestation rates inside and along their buffers. NA, information not available.

Name	Protection Category	Population	Total Area (ha)	Area inside the study area (ha)	Deforestation rate inside the area (1985-2002)	Deforestation rate in the 10-km buffer (1985-2002)
Chiribiquete	PA	0	1 303 829	1 303 829	0.0162	0.0283
Macarena	PA	0	628 052	628 052	0.1695	0.9724
Nukak	PA	0	874 567	874 567	0.0590	0.1418
Puinaway	PA	0	1 115 456	1 115 456	0.0518	0.0707
Tuparro	PA	0	554 401	554 401	0.0620	0.2135
Barranco Colorado	IR	157	9 327	8 353	1.9901	2.8879
Barranquillita	IR	191	22 265	22 265	0.2184	0.1887
Cano Mesetas-Dagua y Murcielago	IR	99	83 720	83 720	0.2247	0.3396
El itilla	IR	44	8 719	8 719	0.1265	0.0890
Group 1 (includes Cano Bachaco Guaripa, La Hormiga y Guacamayas Maipore	IR	279	35 385	34 252	0.2072	1.1916
Grupo 2 (includes Lagos del Dorado, Lagos del paso, Bacat-Arara, Vuelta del Alivio, Yabilla II)	IR	1458	377 530	148 413	0.7644	0.2599
Grupo 3 (includes Barranco Ceiba y Lag., Cano Jabon, Cuenca Media y alta del rio Inirida, Nukak Maku, Parte alta del rio Guainia, Remanso Chorro Bocon, Rios Cuiari e Isana, Tonina-Sejal-San Jose)	IR	5958	6 081 660	3 202 269	0.0933	0.0122
La Fuga	IR	145	8 360	6 215	0.0254	0.0367
La Sal	IR	191	3 275	20 866	0.5839	0.7648
Llanos de Yari (Yaguara II)	IR	196	146 500	91 300	0.8127	1.2362
Piaroa de Cachicamo	IR	NA	16 562	16 562	0.8227	0.5150
Puerto Nare	IR	116	23 368	23 071	0.0041	0.6974
Puerto Viejo y puerto Esperanza	IR	117	9 100	8 973	-0.0349	0.4430
Tucan de Caño Giriza La Palma	IR	290	1 892 207	5 881	0.0422	0.1103