MODELLING RAINFOREST CARBON AND WATER DYNAMICS

-Comparison of different land-use systems following removal of primary forest in the Colombian Amazon-

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Summary

Tropical rainforests play a crucial role in regulating global climate processes, with tropical deforestation potentially having severe adverse effects on both regional and global climate conditions and on the global carbon budget (O’Brien, 1996). The Colombian Amazon is one of the tropical regions that remains poorly studied in terms of deforestation and its effects on the carbon and hydrological cycles. The objective of this study was to develop a simplified model that can simulate basic processes of carbon and water cycling in an undisturbed mature Colombian rainforest, to compare relative trends in carbon and water dynamics under different land-use change scenarios. Modeling data show conclusive evidence that deforestation followed by intensive agriculture (with subsequent pasture development) has long-term effects on net CO$_2$ emissions to the atmosphere. Alternatively, deforestation followed by less-intensive agricultural practices such as shifting cultivation (with subsequent secondary vegetation regrowth) has much shorter and less severe consequences for net CO$_2$ release to the atmosphere, because of carbon conservation induced by secondary forest regrowth. Modeling trends, such as presented in this study, can be of significant use for policy-makers and forest managers in Colombia, because not only does it help to illustrate some of the general impacts of tropical deforestation and land-use systems on global CO$_2$ budgets, but it plays an even greater role in highlighting the need for more detailed and site-specific research addressing carbon and hydrological cycling in the Colombian Amazon rainforest.
1.0 Introduction

Forests play a very important role in terrestrial ecosystem functioning and biogeochemical cycling, by providing watershed protection, minimizing soil erosion, offering specialized habitats for various species, fixing carbon, and regulating regional and global climate (Miller, 1997, p 340), mainly through water, momentum and energy exchange within the atmospheric boundary layer. Tropical rainforests, in particular, have a crucial role in regulating global climate processes, with tropical deforestation potentially having severe adverse effects on both regional and global climate conditions (O'Brien, 1996). Rainfall in the Amazon basin has been recognized as a modulator of convection in the Atlantic Intertropical Convergence Zone, and even over the eastern Pacific (Silva Dias et al., 1987). Zhang et al., (1996), for example, obtained modeling results indicating that diverse deforestation scenarios of the Amazon basin could affect the global atmospheric circulation through perturbations of both the Walker and Hadley circulation cells. Deforestation may influence hydrological cycling by decreasing soil moisture and evapotranspiration, which in turn can increase surface temperatures. Decreased rates in evapotranspiration alone can result in reduced cloud cover, lower precipitation and overall reductions in the long-term mean flow of river systems (Poveda and Mesa, 1996). Such hydrological consequences could in the end alter the availability of freshwater for human and/or animal consumption (Elthair and Brass, 1993; Costa and Foley, 1997).

One of the most important functions of forests is the role they play in global carbon cycling (Melillo et al., 1996). Forests in general contain more carbon per unit area than any other types of vegetation (i.e. croplands, pastures), so that they have the potential to become significant sources of atmospheric CO₂ when forests are cut (Houghton, Skole and Lefkowitz, 1991). According to Melillo et al., (1996), for example, forests contain 20-50 times more carbon than agricultural vegetation. Large-scale removal of forests could result in even greater increases in atmospheric CO₂ than fossil fuel burning alone, which could in turn, contribute to further global warming (Houghton et al., 1983). Replacement of tropical forests with pastures, intensive agricultural croplands, and shifting cultivation were responsible for most of the emissions of carbon to the atmosphere from deforestation in Latin America over the period 1850-1985 (Houghton, Skole and Lefkowitz, 1991). The amount of carbon in secondary vegetation and soils following deforestation is always less than the carbon content of the original forest (Houghton et al., 1983).

The strong possibility of future climate warming arising from anthropogenic activities, has brought the topic of tropical carbon cycling to the forefront of international agendas. Due
to the potential magnitude of atmospheric CO₂ emissions from tropical deforestation, greater
emphasis has been placed on understanding the sources and sinks, as well as the processes
involved in both the global water and carbon cycles. A better understanding of how carbon is
cycled between terrestrial, oceanic and atmospheric reservoirs will ultimately aid policy
makers in decision-making processes regarding international programs and incentives to
reduce anthropogenic CO₂ emissions (Houghton, Skole and Lefkowitz, 1991). One such
incentive involves the placement of economic value to the carbon-fixation capacity of
rainforests (Kenneth, 1998). Costa Rica, for example, has already started programs designed
to sell carbon sequestration capacity of its rainforests to international buyers (Kenneth,
1998).

Despite increased international awareness of the role of tropical forests in global
carbon cycling, there still remains an unsatisfactory understanding of the physical
mechanisms associated with tropical forest CO₂ and water cycling over different temporal
and spatial scales. Estimates of the relative amount of CO₂ released during deforestation
have yet to be made for the Colombian region, for example. The Colombian Amazon
presents a very special case, because it is located in a region of the Amazon Basin with the
highest rates of precipitation and lowest quantities of solar incident radiation (Figueroa and
Nobre, 1990). Some investigators report that from 35-50% of the gross rainfall in the
Amazon Basin is locally generated by recycled water from evapotranspiration from
rainforests (Shuttleworth, 1988; Brubaker et al., 1993; Elthair and Bras, 1994). As the
Colombian Amazon is one of the tropical regions that remains poorly studied in terms of
deforestation and its effects on the carbon and hydrological cycles, this study focuses
particularly on this region (See figure 1).

Figure 1. Map of Colombia. Bogotá and Medellin, the two major cities. Caquetá river, an
important river in the Colombian Amazon.
1.1 Objectives and Research Scope

The objective of this Master’s research was to develop a model that would simulate basic processes of carbon and water cycling in an undisturbed mature rainforest of the Colombian Amazon, in order to compare relative trends in carbon and water dynamics under different land-use change scenarios. Simulation of primary Colombian rainforest was used as the natural (control) scenario, or as the reference point in scenario comparisons. The major land-use systems employed after deforestation in Colombia were simulated with the developed model, including the shifting cultivation practice and growth of secondary forest after abandonment of the agricultural land (scenario A), and intensive agriculture followed by pasture with livestock grazing (scenario B).

The proposed model (called COLCARB) is a very simplified one, designed to provide a tool to help trace relative changes and trends in carbon and water cycling following deforestation in the Colombian Amazon region, trying to capture fundamental aspects of the water and carbon fluxes. One of the major simplifications resides in that detailed analyses of energy balance equations were beyond the scope of the model, although it is recognized that deforestation can have an important effect on energy exchange between the atmosphere and biosphere (i.e. partitioning between latent and sensible heat fluxes, through effects in temperature, albedo, roughness length, and perturbing momentum, energy and moisture fluxes in the atmospheric boundary layer) (O’Brien, 1996). Vegetation-climate feedbacks, indisputably an important tropical deforestation issue, were also not evaluated in this study. Simulation of photosynthetic carbon uptake was correlative, and not mechanistic in design. Average net primary productivity (NPP) values were prescribed for typical rainforests found in the Amazon Basin. Carbon and water flux variables under investigation included net release of \( \text{CO}_2 \), carbon content of litter and soil, moisture content of litter and soil pools, and total overland runoff.

2.0 Theory

2.1 Modeling Assumptions

Water and carbon mass balance calculations are based on differential equations which depend on climatic conditions and a variety of other physical and biological variables. The degree to which each of these variables is accurately parametrized within COLCARB is limited by the following assumptions:
Photosynthetic carbon-uptake in leaves and branches is not mechanistically-modeled, rather average net primary productivity (NPP) values are prescribed for simulated types of vegetation. Consequently, carbon and water sub-models incorporate only litter and soil dynamics.

According to Tobón (pers.comm.), whether mature forests in the Amazon act as net sinks or sources remains uncertain. It is typically assumed that carbon assimilation during the day is in balance with carbon respiration at night, and that all fluxes of carbon occur between the soil and litter pools and the atmosphere. However, growth of secondary forest constitutes a net sink of carbon (Tobón, pers.comm.). Since the model incorporates only litter and soil dynamics, neglecting vegetation carbon uptake, carbon sequestration during the growth of secondary forest cannot be modeled. Instead, a value of carbon uptake by below ground reservoirs is calculated when the secondary forest acts as a net sink of carbon.

There is strong evidence linking changes in vegetation with climate dynamics at local, regional, continental, and global scale (O’Brien, 1996). Even though there remains uncertainty about the magnitude of climatic effects, there is growing consensus that deforestation leads to warmer and drier climates (O’Brien, 1996). COLCARB could be modified in the future to incorporate these important vegetation-atmosphere feedbacks. The model simulates decreases in evaporation and precipitation, neglecting changes in surface temperatures.

The model is simulated on annual time-steps, although there exists important differences in the water flux and energy dynamics during Amazonian dry and rainy seasons. The model attempts to simulate the influence of the annual cycle by a subroutine that creates a season that includes the dry and wet periods within each year. This subroutine allocates different percentages of annual precipitation to each month according to the appropriate season.

Hydrological cycling is a dynamic process, although to simplify simulations, annual monthly average data of precipitation, river flow and climate were prescribed for the period 1961-1988. Prescribed data was obtained from a study of Colombian water balances reported in UNAL-UPME-COLCIENCIAS (1999).

According to Tobón (1999, p.114), 25-30% of evapotranspiration in the Colombian Amazon region arises from evaporation of forest-intercepted moisture, and the remaining 70-75% from the soil via forest transpiration. For simplification purposes, interception loss is not considered in the model, albeit it is an important process in hydrological cycling in humid regions (Sellers, 1992). Precipitation is assumed to fall through the
forest canopy to the ground, and that all water for evapotranspiration comes from litter and soil reservoirs.

Carbon and water flux calculations are based on plots of land which are one hectare in size. Carbon flux values are presented in tons of carbon per hectare per year (t ha\(^{-1}\) yr\(^{-1}\)), and water fluxes in cubic meters of water per hectare per year (m\(^3\) ha\(^{-1}\) yr\(^{-1}\)).

2.2.0 Description of the model

2.2.1 Carbon cycle

COLCARB simulates the flow of carbon through vegetation on the basis of two below-ground carbon reservoirs; fast carbon-recycling within litter and slow carbon recycling within soils. Litter layers in the Colombian Amazon rainforest are found to be typically 7-42 cm thick, with soil layers averaging about 3 m deep (Tobón, 1999, p.162). The depth of fine roots in the Colombian Amazon soils is around 1 m and the little amount of organic matter is found on the first layers of the soil (Tobón, 1999, p.162). Because the fine roots are mainly found around 1 m of depth, soil moisture does not change substantially below this depth. The model assumes a 15 cm fast carbon-turnover litter layer and a 1.5 m slow carbon-turnover soil layer.

COLCARB’s carbon sub-model is based on a modified version of the ecosystem-level carbon storage and flux model presented in Schroeder and Winjum (1995) and Foley (1995) (refer to Figure 2). Vegetation carbon is transferred to other reservoirs in the form of litterfall and root matter. These losses are defined in the model as simply total loss of plant material. The litter reservoir is subject to decomposition, after which, part of the decomposed carbon is released to the atmosphere as CO\(_2\), and the rest is transferred as humus to the soil carbon reservoir (Foley, 1995).

Soil carbon comprises carbon from roots, decomposed carbon from the litter layer and from surplus carbon remaining after soil decomposition. Soil decomposition results in a fraction of soil carbon remaining in the soil reservoir, with the other fraction being respired as CO\(_2\) to the atmosphere.
Figure 2. Flow of carbon through the litter and soil pools as simulated by COLCARB. $C_1$ is the amount of carbon present as litterfall, $C_2$ is the amount of carbon that is decomposed in the litter pool, $C_3$ is the root contribution to the soil pool, $C_4$ is the amount of decomposed carbon that passes from the litter to the soil pool as humus, $C_5$ is the total amount of carbon that decomposes in the soil pool and $C_6$ is the amount of carbon that decomposes in the soil and stays there.

The dynamics of the carbon in the system is presented in terms of a causal feedback loop diagram in Figure 3.

Figure 3. Feedback loops representing carbon dynamics in forests. A positive sign indicates a positive feedback (i.e. an increase in quantity at the beginning of the arrow will cause an increase in quantity at the end of the arrow). A negative sign indicates a negative feedback (i.e. an increase in quantity at the beginning of the arrow will cause a decrease in the amount at the end of the arrow). $B$ indicates that the feedback loop is balanced, which means that after a certain period, the loop will eventually stabilize (Haraldsson, 1999).

**Mathematical equations describing processes of decomposition**

NPP fractions were assigned to stems, branches and leaves (60% of NPP) and root material (40% of NPP) based on Foley's (1995) assessment of carbon allocation in tropical rainforests. During litter decomposition, the model assumed that 80% of the organic matter was released to the atmosphere, with the remaining 20% contributing to soil carbon pools as humus. For soil decomposition, the model assumed that 80% of the organic matter was released to the atmosphere, with the additional 20% remaining as soil carbon. According to Nye and Greenland (1964), in undisturbed tropical forests, litter decomposition results in
between 80 and 90% of the carbon being lost to the atmosphere by oxidation, and for root decomposition, between 50 and 80%.

The mass carbon balance equation used in the model to describe litter carbon content is as follows (also see Figure 2):

\[
\frac{dC_{\text{in. litter}}}{dt} = C_1 - C_2
\]

where \( C_1 \) is the amount of litterfall carbon (t ha\(^{-1}\) year\(^{-1}\)), and \( C_2 \) is the amount of carbon which is decomposed within the litter pool (t ha\(^{-1}\) year\(^{-1}\)).

The mass carbon balance equation used in the model to describe soil carbon is as follows:

\[
\frac{dC_{\text{in. soil}}}{dt} = C_3 + C_4 + C_6 - C_5
\]

where \( C_3 \) is the root contribution to the soil carbon pool (t ha\(^{-1}\) year\(^{-1}\)), \( C_4 \) is the amount of decomposed carbon that is transferred from the litter to the soil pool as humus (t ha\(^{-1}\) year\(^{-1}\)), \( C_5 \) is the total amount of carbon that decomposes in the soil pool (t ha\(^{-1}\) year\(^{-1}\)), and \( C_6 \) is the amount of carbon that decomposes and remains in the soil (t ha\(^{-1}\) year\(^{-1}\)).

According to Walse et al., (1998), rates of decomposition depend on soil and litter chemistry, composition of decomposition substrate, climatic factors such as moisture and temperature, presence of decomposing organisms, chemical factors such as pH, aluminum content, and nitrogen and phosphorous concentration in the soil solution. For simplification purposes, COLCARB considers only the physical factors that cause breakdown of litter organic matter, which include moisture and temperature. The model incorporates moisture and temperature rate-regulating functions presented by Walse et al., (1998) (see below):

\[
r = K_{pot} \cdot m \cdot F(w) \cdot J(T)
\]

where \( r \) is the mass loss-rate of organic material (t ha\(^{-1}\) yr\(^{-1}\)), \( K_{pot} \) is a potential rate constant expressed as year\(^{-1}\), \( F(w) \) and \( J(T) \) are moisture and temperature rate-regulating functions, respectively.

The equation used in the model to describe moisture rate-regulation is based on the assumption that decomposition follows a Langmuir adsorption isotherm for physical adsorption of water to a particulate solid (Walse et al., 1998), which is defined below:

\[
F(w) = \frac{K_w \cdot W^p}{1 + K_w \cdot W^p}
\]
where $K_w$ is an adsorption coefficient, $v$ is the adsorption order and $W$ is the relative soil or litter moisture saturation (defined as the ratio between soil or litter moisture content and the maximum soil or litter moisture holding capacity) (Walse et al., 1998).

The equation used in the model to describe the impact of temperature on decomposition rate assumes that biological decomposition varies with temperature according to an Arrhenius expression (Walse et al., 1998), and is as follows:

$$J(T) = \exp\left(\frac{E_a}{R*T_r} - \frac{E_a}{R*T}\right)$$  \hspace{1cm} (5)

where $E_a$ is activation energy (J mol$^{-1}$), $T_r$ is reference temperature in degrees K, $T$ is temperature in degrees K, and $R$ is the universal gas constant (J mol$^{-1}$ K$^{-1}$) (Walse et al., 1998).

Constants prescribed for activation energy ($E_a$), adsorption coefficient ($K_w$), adsorption order ($v$), and $K_{pot}$ for slow and fast carbon-recycling pools are listed in Table 1. Refer to Walse et al., (1998) for a description of the methodologies used to estimate decomposition equation parameters.

Table 1. Constants used for calculation of the litter and soil decomposition from Walse et al., (1998). Parameters were calibrated according to the carbon content of vegetation and soil reservoirs reported by Foley (1995).

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>LITTER</th>
<th>SOIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_a/R$</td>
<td>1500</td>
<td>2689</td>
</tr>
<tr>
<td>$T_r$ ($^\circ$C)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>$T$</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>$K_w$</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>$v$</td>
<td>9.4</td>
<td>9.4</td>
</tr>
<tr>
<td>$K_{pot}$ (year$^{-1}$)</td>
<td>36.5</td>
<td>1.36</td>
</tr>
</tbody>
</table>

Air temperatures in the Amazon region in Colombia are uniform due to the homogeneous relief, ranging from 24-28$^\circ$C throughout the year (IDEAM, 1999 a). Since temperature rate regulating factors calculated for litter and soil decomposition are not greatly changed within this temperature range, temperature was assumed to be constant and equal to 27$^\circ$C during soil and litter decomposition.
2.2.2. Hydrological Cycling

The hydrological sub-model, like that of carbon, has two primary water reservoirs; litter and soil moisture (see Figure 4). The water-flux submodel in COLCARB contains two hydrological input variables (precipitation and potential evapotranspiration) and four hydrological output variables (litter and soil moisture, actual evapotranspiration and runoff).

The process of evapotranspiration is defined as the upward flux of water into the atmosphere from the soil (evaporation) and from the stomata of leaf tissue (transpiration) (Reading, Thompson, and Millington, 1995, p.236). Rainfall initially falls to the ground (i.e. litterfall pool), but will eventually seep down into the underlying soil reservoir. The uppermost layers of soil in the Amazon are porous and therefore permit fast infiltration of rainfall (Souza et al., 1996). From the water that penetrates the litter layer, a small percentage will eventually leave the pool as evapotranspiration, with the remainder of water stored as litter moisture. Once the saturation point of the litter layer is reached, percolation to the below-ground soil pool will take place. A fraction of the water entering the soil is lost during evaporation, but the remainder will stay and contribute to soil moisture content. When maximum water-holding capacity of the soil is finally reached, water will leave the soil reservoir as overland runoff (Noij et al., 1993, p.18).

Precipitation falling in the Amazon Basin consists of a recycled water component which is derived from local evapotranspiration, and from an imported water component which contains moisture transported from surrounding regions and from oceanic sources (Poveda and Mesa, 1996). According to Shuttleworth (1988), Brubaker et al., (1993) Elthair and Bras (1994), and Nobre (pers.comm.) the local recycled contribution to Amazon precipitation is probably between 35 and 50%. Under Natural (or control) simulations, the model assumes that 50% of gross rainfall is locally generated. For deforestation scenarios (scenarios A and B), values of recycled precipitation change according to the type of land-use that is institutionalized after forest removal (i.e. pasture or agriculture). COLCARB does not model forest canopy interception explicitly, therefore evaporation and transpiration processes are based on moisture contained in litter and soil pools.
Figure 4. Water fluxes simulated in the hydrological sub-model of COLCARB.

Water dynamics in the forest are presented as causal feedback loops in Figure 5. Litter layers in the Colombian Amazon basin typically saturate with low amounts of water (Tobón, 1999, p.78). For a litter layer of 15 cm thickness, the minimum amount of water needed for saturation is approximately 15 mm (Tobón, 1999, p.78). Therefore, an increase or a decrease in precipitation minimally affects litter moisture, unless extreme dry conditions were to occur, such as those prevailing during El Niño events (Poveda and Mesa, 1997). Overall, Amazonian soils exhibit low water-holding capacities, which indicates that they require low amounts of water to saturate (Tobón, 1999, p.78). A high proportion of the precipitation falling in the Amazon Basin, therefore, exits the forest ecosystem as overland runoff (Tobón, 1999, p.71).

Figure 5. Causal feedback loop diagram incorporated in COLCARB’S hydrological submodel. B indicates that the causal feedback loop is balanced, meaning that after a certain period, the feedback loop will eventually stabilize (Haraldsson, 1999).
Equations describing water flows and processes of evapotranspiration

Equations describing water fluxes in the model contain the following parameters: precipitation, maximum water-holding capacities of litter and soil pools, hydraulic conductivities used for calculating percolation and runoff values, and potential evapotranspiration. Based on these parameters and the following set of hydrological equations, COLCARB calculates values for litter and soil relative moisture content (m³ ha⁻¹ / m³ ha⁻¹), real evapotranspiration (m³ ha⁻¹ yr⁻¹), and runoff (m³ ha⁻¹ yr⁻¹).

Mass balances equations used in the model to describe litter and soil water content are as follows:

\[ \frac{dS_{\text{litter}}}{dt} = P - ET_{\text{litter}} - P_e \] (6)

\[ \frac{dS_{\text{soil}}}{dt} = P_e - ET_{\text{soil}} - \text{Runoff} \] (7)

where \( S_{\text{litter}} \) and \( S_{\text{soil}} \) are the amount of water in the litter and soil reservoirs, respectively (m³ ha⁻¹), \( P \) is precipitation (m³ ha⁻¹ yr⁻¹), \( ET_{\text{litter}} \) is evapotranspiration from litter and \( ET_{\text{soil}} \) is evapotranspiration from the soil reservoir (m³ ha⁻¹ yr⁻¹), and \( P_e \) is the flow of water from the litter to the soil pool (m³ ha⁻¹ yr⁻¹).

Evapotranspiration from both soil and litter pools is calculated in the model as a fraction of the potential evapotranspiration (UNAL-UPME-COLCIENCIAS, 1999), which is dependent on two important factors: first, on the relative moisture content of soil and litter which relates to the evaporation contribution of evapotranspiration, and second, the type of vegetation which relates to the transpiration contribution of evapotranspiration. Availability of energy and moisture content are the main controlling factors of evapotranspiration (Ward, 1975, p.99). Apart from factors such as soil water availability, climate, and energy available at leaf surfaces, transpiration is fundamentally dependent on plant cover type (Ward, 1975, p.99).

In Northwest Amazonia, studies show that litter contributions to transpiration vary from 15-28% of actual transpiration, and that soil contributions vary from 65-83% (Tobón, 1999, p.113). The model assumes that 20 and 80% of total evapotranspiration are litter and soil contributions, respectively.

The equation used in the model to calculate rates of evapotranspiration is as follows:

\[ ET = Ep \cdot \left( \left( \frac{S}{W} \right)^{0.5} + V_F \right) \] (8)
where \( ET \) is the actual evapotranspiration (m\(^3\) ha\(^{-1}\) yr\(^{-1}\)), \( E_p \) is potential evapotranspiration (m\(^3\) ha\(^{-1}\) yr\(^{-1}\)), \( S \) is soil or litter water content (m\(^3\) ha\(^{-1}\)), \( W \) is the maximum water-holding capacity for soil or litter (m\(^3\) ha\(^{-1}\)), and \( V_F \) is a vegetation factor constant.

Maximum water-holding capacities observed for the Amazon Basin are in the order of 10.5 ± 7.5 mm for litter layers of 7-23 cm thickness, and values of 520-600 mm for soil layers of 1.5 m (Tobón, 1999, p.78). COLCARB models hydrological cycling with the following water-holding capacities: 148.5 m\(^3\) ha\(^{-1}\) for a litter layer 15 cm thick, and 5250 m\(^3\) ha\(^{-1}\) for a soil layer 1.5 m in thickness. Because of the optimal environmental conditions found within the Amazon region, particularly the high availability of litter and soil moisture, actual transpiration is very similar to potential transpiration, especially during the rainy season (Tobón, 1999). Only during very dry periods, specifically in January and February, does actual transpiration become between 60 and 90% of potential transpiration (Tobón, 1999, p.114). Correspondingly, values for the vegetation factor (\( V_F \) in equation 8), were adjusted to obtain values of actual evapotranspiration close to potential evapotranspiration during the rainy season, and lower values during the dry season. The model uses values of 4.5 and 3.5 for litter and soil evapotranspiration calculations, respectively.

One of the major consequences of deforestation is a reduction in evapotranspiration (Poveda and Mesa, 1996; Manzi and Planton, 1996; Dias and Reignier, 1996; Lean et al., 1996). For deforestation scenarios (i.e. scenarios A and B), the model assumes reductions in evapotranspiration, depending on the land-use system that was adopted after deforestation. These reductions in evapotranspiration are presented in sections 3.3.2.1 and 3.3.2.2.

Water flux between the soil and litter profile depends mainly on hydraulic conductivity, which in turn is influenced by pore size distribution and water content (Waring and Running, 1998, p.51). Hydraulic conductivity of soils decreases very quickly with concomitant reductions in relative soil moisture. Water fluxes between litter, soil and overland runoff are calculated in COLCARB using the following equation (Waring and Running, 1998, p.51):

\[
F = K^* \left( \frac{\theta}{\theta_{sat}} \right)^\beta \tag{9}
\]

where \( K \) is the unsaturated hydraulic conductivity of the litter or soil (m\(^3\) ha\(^{-1}\) yr\(^{-1}\)), \( \theta/\theta_{sat} \) is the relative moisture coefficient, and \( \beta \) is an empirical constant which depends on soil texture. \( K, \beta, \) and \( \theta_{sat} \) describe water-holding properties of the soil and litter, as well as its ability to provide water for evapotranspiration. \( K, \beta, \) and \( \theta_{sat} \), therefore, depend on type and texture of soil and litter organic matter (Tomassella and Hodnet, 1996).
There is lack of data concerning the litter and soil hydraulic properties within the Amazon Basin, and even less known about how they change as a result of deforestation (Tomasella and Hodnett, 1996). K-values for litter and soil were calculated from data collected for the Caquetá river in Colombia, which has been a site of intensive deforestation in the past (see Figure 1) (Tobón, pers.comm). Riverflow data from Caquetá corresponds to prescribed levels of precipitation and potential evapotranspiration used in COLCARB. Because litter and soil have different conductivities based on their composition and physical properties (Tobón, 1999, p.10), the model incorporates a K-value (K1) for water flowing from the litter to the soil pool, and a K-value (K2) for water leaving the soil pool (See Table 2).

General Circulation Models (GCMs) typically model land surfaces having between 3 and 6 soil layers, in order that vertical distribution of soil moisture and resultant runoff can be accurately simulated (Sellers, 1992). Because COLCARB contains a very simplified (two-layer, soil and litter) hydrological submodel, it was necessary to incorporate two K-values, one specific to the dry season and the other specific to the wet season, in an attempt to obtain realistic values of overland runoff (see Table 2).

In calculating water flux between litter, soil and overland runoff, the model incorporated litter and soil relative moisture contents between 0.2 and 0.3 (m³ ha⁻¹/m³ ha⁻¹) and between 0.3 and 0.45 (m³ ha⁻¹/m³ ha⁻¹), respectively, as presented by Souza et al., (1996). The model assumed a β-value of 2.0 because low β-values represent soils with low water-retention capacities and rapid drainage potential (Sellers, 1992).

Table 2. Unsaturated hydraulic conductivities for litter (K₁) and soil (K₂). Low-flow values of K₁ and K₂ correspond to hydrological conditions observed in January, February and December. High-flow values of K₁ and K₂ are used for other months of the year.

<table>
<thead>
<tr>
<th></th>
<th>K₁ (m³/ha year⁻¹)</th>
<th>K₂ (m³/ha-year⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low flow</td>
<td>23600</td>
<td>4200</td>
</tr>
<tr>
<td>High flow</td>
<td>39600</td>
<td>15500</td>
</tr>
</tbody>
</table>

2.2.3 Integrated carbon and hydrological sub-models

COLCARB's carbon and hydrological submodels are integrated via equations describing rates of soil and litter decomposition. Decomposition of litter and soil organic matter is enhanced by moisture content of the soil and litter surface profiles (Houghton et al., 1983), up to the point of soil-water saturation. Anaerobic conditions (i.e. waterlogged
soils) impede decomposition and preserve fossil organic matter. An increase in litter and soil moisture will increase the bulk mass of carbon in decomposition which will result in an increase of \( \text{CO}_2 \) released. Water and carbon dynamics in the forest are presented in terms of feedback loops in Figure 6.

![Causal loop diagram identifying positive and negative feedbacks involved in carbon and water flow within a rainforest.](image)

**Figure 6.** Causal loop diagram identifying positive and negative feedbacks involved in carbon and water flow within a rainforest. A positive sign indicates a positive feedback (i.e. an increase in quantity at the beginning of the arrow will cause an increase in quantity at the end of the arrow). A negative sign indicates a negative feedback (i.e. an increase in quantity at the beginning of the arrow will cause a decrease in the amount at the end of the arrow. B indicates that the feedback loop is balanced, which means that after a certain period, the loop will eventually stabilize (Haraldsson, 1999). ET is defined as evapotranspiration.

### 2.3 Deforestation

Deforestation rates in Colombia have been estimated in the order of 600,000 ha yr\(^{-1}\) and have occurred mainly in the Andean and Amazonian regions (MMA, 1999). The primary causes of Colombian deforestation are (listed in order of importance): expansion of agricultural and livestock grazing boundaries (73%), production of timber for industry and commerce (12%), consumption of firewood (11%), natural forest fires (2%), and illicit (coca and amapola) cultivation (2%) (CGR, 1997, p 39). Because agriculture and pasture have been two of the most important land-use changes in Colombia over the last four decades, they were selected as applications for the COLCARB model.

One of the influences of deforestation on the hydrological cycle is the reduction in evapotranspiration, which in turn can lead to reductions in regional precipitation (Manzi and Planton, 1996; Dias and Reignier, 1996; Lean et al., 1996; Elthair and Bras, 1993; Poveda and Mesa, 1996). If moisture advected from oceans and surrounding areas is kept constant, (which is a major simplification) then gross rainfall will decrease as a result of reduced internal moisture recycling. Litter in the Amazon forest has a low saturation point (Tobón,
1999, p.78), which means that a decrease in total precipitation will have minimal to no affect on litter moisture content. Decreased rainfall, however, will affect soil moisture and ultimately influence overland runoff and river flow. A decrease in soil moisture will decrease the bulk mass in decomposition in the soil pool.

Deforestation also has a significant influence on regional (and potentially global) carbon budgets. Carbon dioxide is first released to the atmosphere via burning at the time of cutting, and will eventually be released through exponential decay of charred tree logs and decomposition of soil organic matter during the years following deforestation (Melillo et al., 1996). Cultivation of forest soils after deforestation can have a further affect on terrestrial carbon balance. According to Melillo et al., (1996), around 25% of the above-ground carbon is lost to the atmosphere when the forest is removed and the land is cultivated.

The behavior of the system when removal of the forest and other land uses take place is presented in terms of feedback loops in Figure 7. Once the land is deforested, the logs are left on the ground exposed to decomposition. In Figure 7, this is represented by the arrow that goes from deforestation to carbon in litter. An increase in deforestation will cause an increase in carbon in the litter pool due to the logs left on the ground. This loop is predominant immediately after deforestation, speeding up decomposition and CO₂ releases to the atmosphere. As a result of the increase in carbon in the litter pool, an increase in carbon in the soil pool is also expected. Once other types of vegetation grow in the deforested area (i.e. agricultural crops or pasture), the loop that goes from Forest/other land uses to carbon in litter will be predominant. Carbon in litter and soil will increase depending on the amount of carbon in the type of vegetation present. At the hydrological level, when the forest is removed, the local contribution to precipitation will decrease as a result of decreases in evapotranspiration. Consequently, reductions in litter and soil moisture, and in runoff are expected.

Figure 7. Causal loop diagram describing the positive and negative feedbacks on carbon and water cycling following deforestation. A positive sign indicates a positive feedback. A negative sign indicates a negative feedback. B indicates that the feedback loop is balanced.
3.0 Methodology

3.1 Modeling Tool

COLCARB was programmed using the STELLA system dynamics development environment.

3.2 Site

Hydrological data used for COLCARB simulations were obtained from studies of the Caquetá River (UNAL-UPME-COLCIENCIAS, 1999), an important river basin located in the Colombian Amazon (See Figure 1). The northern watershed region has been subject to severe deforestation and has lost approximately 70% of its original rainforest cover (Tobón, 1999, p.3.). Although the model does not simulate carbon and water dynamics of specific sites, it is assumed that data generated by the model pertain to the northern Caquetá watershed region.

3.3 Experimental design

3.3.1 Natural (control) scenario

The natural scenario simulates carbon and water dynamics in a late-successional tropical primary rainforest which has been left undisturbed by human activity. Carbon dynamics in the Natural (control) scenario were modeled on the basis of Amazonian rainforest NPP values of 12 t of C ha\(^{-1}\) yr\(^{-1}\), as described in Foley (1995).

3.3.2 Deforestation (common to both scenarios A and B)

As a result of clear-cutting and burning, a portion of forest biomass will be consumed by fire and emitted to the atmosphere as CO\(_2\), and a portion will remain on the ground as charcoal and ash (Lima de Alencastro, Fearnside and Cerri, 1999). Any biomass surviving burning can undergo decomposition or re-burning, depending on the land-use system employed after deforestation (Lima de Alencastro, Fearnside and Cerri, 1999). For COLCARB simulations, it is assumed that biomass surviving the burn will not undergo re-burning, but will solely remain available for decomposition. Vegetation litter layers are completely removed during burning (Tobón, 1999, p.17). For COLCARB simulations, any biomass surviving the initial burn (i.e. ash, charcoal and unburned logs) became the new
litter layer, thus was available for decomposition. Afterwards, any litterfall contribution to the litter reservoir depended on the type of vegetation currently occupying the site.

According to De Salas (1978) 10-16% of total carbon present is volatilized following forest burning in Colombia. COLCARB was programmed with 16% of carbon loss following the burning of the mature forest, so that 84% of forest biomass was assumed to remain as unburned logs, charcoal and ash and contribute to the litter carbon layer.

3.3.2.1 Scenario A

Studies show that shifting cultivation lasting between 3 and 5 years is common practice in the tropics (Houghton et al., 1991; Tobón, 1999 p.17). Scenario A simulations were divided into five stages defined as the following: a) simulation of 40-years of undisturbed primary rainforest, b) deforestation and biomass burning, c) 5-years of shifting cultivation, d) 20-years of secondary forest growth, and e) secondary forest growth until the forest recovers 80% of its initial carbon content. The model simulates the initial 40-years of undisturbed primary rainforest incorporating carbon and hydrological parameters used in natural (control) simulations. Deforestation and burning parameters are described in section 3.3.2. Agricultural crops result in a very thin layer of leaves, shrubs, and foliage, therefore during the 5-years of shifting cultivation, the model incorporated litter layers containing carbon in the amount of 10% of agricultural crop NPP.

Amazon soils have low availability of nutrients, therefore soil degradation occurs following only a few years of cultivation (Abaunza and Tobón, 1994, p.17 ). COLCARB simulations were based on the assumption that crop NPP varies during the 5-years of cultivation; growing very fast at the beginning of the period until reaching its maximum potential, and then decreasing to a minimum value at which point the soil is no longer productive for agriculture (see Figure 8 for hypothetical soil productivity curve). The hypothetical soil productivity curve was produced using a Stella function which allowed graphs to be introduced into the model. Values of NPP used during the 5-years of agriculture are presented in Appendix A. Because of a lack of information describing NPP ranges for Colombian agricultural crop species, maximum crop NPP for the 5-year period of shifting cultivation was defined as being 70% of primary forest NPP. The minimum value was assumed to be 35% of primary forest NPP.

In reality, partial abandonment of crop lands occurs as soils begin to degrade, although it takes been 15 to 20 years for agricultural land to be completely abandoned (Tobón, 1999, p.17). COLCARB simulations were performed based on the assumption that
land is totally abandoned after 5-years of shifting cultivation, thus permitting successional vegetation to begin growing immediately after the end of this period.

Figure 8. Pattern of NPP of crop during the 5 years of cultivation. The highest value is reached during the first years, followed by a decrease until a minimum at which the successional vegetation starts to grow after abandonment of the land.

A change in land-use from primary rainforest to shifting cultivation affects hydrological cycling, and so was simulated by COLCARB for scenario A under the following conditions. Lacking information about evapotranspiration rates of Colombian agricultural crop species, COLCARB simulations were conducted under the assumption of a 25% reduction in actual evapotranspiration. Because a reduction in evapotranspiration will lead to reduced internal water-recycling and therefore precipitation, keeping constant the imported contribution to precipitation, total precipitation amounts are assumed to be reduced by 25%. For simplification purposes, the model reduced total evapotranspiration instead of potential evapotranspiration during the shifting cultivation period. Values of potential evapotranspiration and the vegetation factor (V.F.) in equation (8) were assumed to be similar to those for mature rainforest. Since potential evapotranspiration is mainly controlled by meteorological factors and actual evapotranspiration is also affected by meteorological factors but mainly affected by vegetation and soil factors (Ward, 1975, p.99), when the forest is removed, and meteorological factors are constant, actual evapotranspiration will change.

Since the litter layer present during agriculture is very thin, the model assumed a 10 and 90% contribution to total evapotranspiration from the litter and soil pools, respectively. Because total evapotranspiration was reduced by 25%, litter and soil contributions to evapotranspiration were also assumed to be reduced by 25%. For simplification purposes, all other parameters used in calculations during the hydrological subroutine (i.e. K-values for calculations of runoff and drainage of water from the litter to the soil pool, and soil water-holding capacities) were assumed to be the same as for primary forest.
Secondary forest starts establishing once shifting-cultivation practices are ceased. According to Tobón (1999, p.17), successional vegetation biomass increases exponentially during the first 20-years of growth because native species can uptake soil nutrients more efficient than crops. During this 20-year period, model simulations were based on the assumption that this exponential growth reaches a maximum value of 70% of primary forest NPP. Although secondary forest growth has been shown to behave as a net sink of carbon (Tobón, pers.comm), COLCARB did not model above-ground carbon sequestration, rather, below ground-carbon uptake was simulated. Litterfall and root contributions to litter and soil carbon pools, respectively, were assumed to be 40 and 60% of primary forest NPP. A summary of the NPP values used during model simulations of successional forest is presented in Appendix A.

Hydrological cycling in successional forest is different than for mature forest, thus COLCARB simulated these changes under the following assumptions. Evapotranspiration and its contribution to regional water re-cycling increased concurrently with successional forest growth. This response was simulated in the model using a Stella function which allows for graphs to be incorporated into models. Modeled increases in evapotranspiration during the initial 20-years of successional growth are presented in Appendix A. Following this 20-year period, COLCARB assumed that secondary forest will reach its maximum evapotranspiration potential at a value equaling the maximum evapotranspiration rate attained for mature rainforest.

For simplification purposes, COLCARB increased actual evapotranspiration instead of potential evapotranspiration, therefore values for potential evapotranspiration and the vegetation factor (V.F.) in equation (8) were assumed to be the same as for mature forest. As in the mature forest, at this stage, both the litter and soil pools are assumed to contribute to total evapotranspiration with 20 and 80% respectively. For simplification purposes, the remaining parameters for the hydrological model are assumed to be the same as used when the forest is present. Those parameters are, K values for calculation of runoff and drainage of water from the litter to the soil pool, and water holding capacities.

COLCARB was built based on the assumption that successional forest will require 100-years for biomass to recover 80% of its initial value, evidenced by data reported by Tobón (1999, p.17). COLCARB increased secondary forest NPP slowly until it reached 80% of primary forest NPP (See Appendix A). Litter and root contributions to litter and soil carbon pools remained at 60 and 40%, respectively, of successional forest NPP. For the period of secondary forest growth, it was assumed that hydrological cycling will proceed in a
similar manner as for primary rainforest (i.e. similar hydrological parameters were used for both vegetation types).

3.3.2.2 Scenario B

COLCARB scenario B simulations were divided into four stages as follows: a) simulation of 40-years of undisturbed mature forest, b) deforestation and biomass burning, c) 10-years of intensive agriculture, d) growth of pasture and intensive livestock grazing for 50- years. The methodology used to simulate stages a and b (above) was the same as for scenario A.

During the 10-year period of intensive agriculture, undesired vegetation is removed and land is continuously cultivated with traditional crop species such as plátano, yuca, and fruits among others (Tobón, 1999, p.17). Because Amazonian soils are initially poor in nutrients, after 10-years of intensive agriculture, resulting soils are so much degraded that the land can only be used as pasture (Tobón, 1999, p.17). Similar to scenario A, crop NPP is assumed to reach its maximum during the first years of cultivation at a value equivalent to 70% of primary forest NPP. Minimum crop NPP's were reached at the end of the 10-year period and attain a value assumed to be only 18% of primary forest NPP. The shape of the hypothetical NPP response-curve over time is the same as for scenario A (see Figure 8), although minimum values differ. A summary of the crop NPP values used during the simulation of intensive agriculture is presented in Appendix A.

For simplification purposes, several hydrological parameters used during the simulation of intensive agriculture were assumed to be the same as for primary rainforest. These parameters include K-values for calculation of runoff and drainage of water from litter to soil pools, soil and litter water-holding capacities, and potential evapotranspiration. The following parameters used in simulations of intensive agriculture were assumed to be the same as for shifting cultivation (i.e. scenario A): reductions in precipitation and actual evapotranspiration, litter and soil contributions to evapotranspiration, and NPP contribution to litter and soil organic matter.

Livestock grazing in the Amazon typically involves a practice of annual burning during the dry season to obtain specified types of pasture (Tobón, 1999, p.17). The yearly burn of pasture is simulated with a volatilization loss of 16% (De Salas, 1978) and with the litter layer as the amount of biomass burned. So, each year, the model releases 16% of the carbon litter pool to the atmosphere.

Lacking information about pasture NPP in the tropics and in Colombia in specific, pasture NPP was assumed to be 18% of primary forest NPP. Carbon content of pasture
litterfall was assumed to be equivalent to 10% of pasture NPP. Roots were assumed to contribute to soil carbon with 90% of pasture NPP. Actual evapotranspiration was assumed to decrease by 35% of primary forest evapotranspiration, subsequently leading to a 35% reduction in total rainfall keeping constant the imported precipitation. Litter and soil contributions to evapotranspiration were assumed to be 10 and 90%, respectively.

For simplification purposes, several hydrological parameters used during model simulations of pasture development were assumed to be the same as for primary forest. These parameters include K-values for calculations of runoff and drainage of water from litter to soil pools, soil water-holding capacities, and potential evapotranspiration.

4 Results and discussion

4.1 Results

Net carbon released to the atmosphere

Net carbon released to the atmosphere is calculated by the model as the difference between vegetation carbon uptake minus both carbon released during litter and soil decomposition and during biomass burning. Net carbon emissions for the Natural (control) scenario, scenario A and scenario B plotted over time are shown in Figure 9. Any horizontal line represents a zero net release of CO$_2$, with other line configurations depicting either a positive or negative uptake of CO$_2$.

![Figure 9. Net carbon released to the atmosphere by Natural scenario, scenario A and scenario B.](image)

After stabilization, net carbon emissions in the control scenario remain at or around zero. For the first 40-years, net CO$_2$ emissions for scenarios A and B are the same as for control simulations (i.e. around zero) because emissions are based on carbon dynamics of primary forest cover.
Following replacement of forest with agricultural plants in scenario A, net emissions of CO$_2$ to the atmosphere increase rapidly to a maximum and then slowly begin to decrease. The initial rapid increase in CO$_2$ emissions is primarily due to carbon emitted during biomass burning and rapid decomposition of charcoal litter. According to Houghton, Skole and Lefkowitz (1991), after forest clearance, 95% of above-ground biomass decomposes exponentially within the first 5-years of land-use. In COLCARB, most of the remaining unburned biomass decomposes after 4-years. The smaller second pulse of CO$_2$ emissions occurs mainly as a result of soil decomposition during the shifting cultivation phase. Thin litter layers also contribute to decomposition, but on a much smaller scale during the cultivation period. The slow decline in CO$_2$ emissions (indicating carbon removal from the atmosphere, i.e. atmospheric CO$_2$ sink) results from growth of secondary forest vegetation. Because COLCARB simulates secondary forest which reaches only 80% of NPP, steady-state carbon emissions cannot be simulated.

Following forest clearance in scenario B, net CO$_2$ emissions rapidly increase as a result of biomass burning and rapid decomposition of unburned charcoal. Following that rapid increase, a slower increase continues during the intensive agriculture period and then during the extensive livestock grazing of pasture period. Because pasture litter layers are very thin (i.e. a carbon content of 10% of pasture NPP), decomposition of soil reservoirs is primarily responsible for this net CO$_2$ emission.

The rapid decomposition of unburned charcoal during the first 4-years of changed land-use in scenarios A and B is likely a model artefact (i.e. due to parametrizations used in COLCARB) because COLCARB does not incorporate all of the variables important for decomposition, including decomposing organisms, substrate quality and chemical properties of litter and soil. The expected pattern of this line should be less steep because decomposition of 95% of aboveground biomass is expected to last between 6-10 years. (Houghton, Skole and Lefkowitz, 1991). Additionally, errors may also be introduced because the temperature-dependence of decomposition is modeled assuming constant temperature during simulations.

Net carbon emissions caused by deforestation disturbances during scenario A are calculated as the difference between the value simulated at time=82years (i.e. period of deforestation and land use disturbances and also subsequent years when carbon emissions are greater than uptakes) minus the value at time=40years, just prior to disturbance (see Table 3). Results indicates that it takes secondary forest 37 years to begin acting as a net sink of atmospheric carbon. Even though carbon sequestration by vegetation was not explicitly modeled, the model simulated below-ground carbon-uptake during the phase of secondary forest growth. The total quantity of carbon sequestered by the below-ground component of
secondary forest (once it's become a net sink for carbon) is calculated as the difference between the value of net emissions when the secondary forest acts as a sink (time=82 years) minus the last value of the simulation of secondary forest (year=150), and corresponds to a value of 6.4 t ha\(^{-1}\). Net carbon emissions caused by disturbances in scenario B are calculated as the difference between the value reached when pasture is present minus net emissions of the undisturbed primary forest. See Table 3.

As expected, Scenario B net emissions are higher than those in scenario A. Although, only by 6%. Values obtained for net emissions in Scenario B may have been expected to be much higher than in scenario A. However, the small difference obtained can be explained from the fact that during the period of pasture cultivation, soil moisture decreases by 16-21\% if compared to natural (control) conditions, and as a result, decomposition rates also decrease. Consequently, net emissions are slower during the pasture period, which means that CO\(_2\) releases through decomposition will take longer periods of time. As COLCARB pasture period is simulated during 50-years, release of CO\(_2\) afterwards is not included. Burning pasture could be expected to contribute with a high percentage to net emissions. Instead, it contributes only with 1.5% every year, as it is only the litter layer being burned and the litter layer contains only 10\% of pasture NPP.

Table 3. Carbon emissions to the atmosphere for Natural (control), scenario A and scenario B simulations by COLCARB.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Net Emissions during the period of disturbance and subsequent years when carbon emissions are greater than uptakes. [t ha(^{-1})]</th>
<th>Period of disturbance and subsequent years when carbon emissions are greater than uptakes. [year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural (control)</td>
<td>≈ 0</td>
<td>0</td>
</tr>
<tr>
<td>A</td>
<td>232</td>
<td>40-82</td>
</tr>
<tr>
<td>B</td>
<td>246</td>
<td>50-100</td>
</tr>
</tbody>
</table>

A comparison of carbon releases by other anthropogenic sources in Colombia is presented below assuming different amounts of deforested areas (See Table 4 and Table 5). Based on the still forested area in the Colombian Amazon (39400000 ha) (MMA, 1999) net emissions for scenario A and B were calculated, assuming 10, 20, 30, 50 and 100 % removal of the forest in a year. Net emissions were also calculated based on the reported actual deforestation rates in Colombia (600000 ha year\(^{-1}\)) (MMA, 1999). To be able to compare other anthropogenic emissions and the emissions caused after deforestation and land-use changes, it was necessary to get an annual average of net emissions caused by deforestation. Therefore, net emissions in scenario A and B were divided into the number of years they...
occurred. As a result, the calculated annual average CO$_2$ emissions for scenario A and B were 5.4 t C ha$^{-1}$ and 4.8 t C ha$^{-1}$ respectively. As the period of land disturbances in scenario A is shorter, the annual average net emissions calculated for scenario A are larger than for scenario B. It is important to emphasize that these values are only averages, and that real emissions for scenario B are larger due to the long term effects of land uses in this scenario. Emissions data used from other anthropogenic sources and from deforestation and land use change in Colombia correspond to year 1990 (IDEAM, 1999, b).

Table 4. Different estimates of average net emissions for scenario A and B for different amounts of deforested areas.

<table>
<thead>
<tr>
<th>Deforested area</th>
<th>Net emissions Scenario A [M t/year]</th>
<th>Net emissions Scenario B [M t/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>actual deforested area per year (6000000 ha)</td>
<td>3.3</td>
<td>2.9</td>
</tr>
<tr>
<td>10% of forested area</td>
<td>21.3</td>
<td>18.9</td>
</tr>
<tr>
<td>20% of forested area</td>
<td>42.8</td>
<td>38</td>
</tr>
<tr>
<td>30% of forested area</td>
<td>64.2</td>
<td>57</td>
</tr>
<tr>
<td>50% of forested area</td>
<td>106.9</td>
<td>95</td>
</tr>
<tr>
<td>100% of forested area</td>
<td>213.9</td>
<td>189.9</td>
</tr>
</tbody>
</table>

Table 5. CO$_2$ emissions from other anthropogenic sources in Colombia during 1990.

<table>
<thead>
<tr>
<th>Other CO$_2$ anthropogenic sources</th>
<th>1990 emissions * [M t/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transports</td>
<td>14.9</td>
</tr>
<tr>
<td>Industry</td>
<td>27.5</td>
</tr>
<tr>
<td>Deforestation and land use changes</td>
<td>4.1</td>
</tr>
<tr>
<td>* (IDEAM, 1999, b).</td>
<td></td>
</tr>
</tbody>
</table>

Based on the average annual net emissions calculated for scenario A and B, values obtained in table 4 show that as soon as deforestation reaches 10% of the total forested area, CO$_2$ emissions due to deforestation and its subsequent land-use change will be higher and very close to other anthropogenic CO$_2$ sources. If deforestation rates continue being 600000 ha year$^{-1}$ as it is now, in 6.5 years, 10% of the forested area will be already lost. If 20% of the Colombian amazon forest is lost in a year, according to scenario A and scenario B calculations by COLCARB, CO$_2$ emissions by deforestation will equal total CO$_2$ emissions produced by other anthropogenic sources in the country.

Soil carbon storage

After 100-years, simulated (primary rainforest) soil carbon stabilizes in the control scenario at a value of 101.15 ± 0.15 t C ha$^{-1}$ (see Figure 10), which is in accordance with the value of 101.17 t C ha$^{-1}$, presented by Foley (1995).

For scenario A, soil carbon during the shifting-cultivation phase is simulated to rapidly increase by 31% at year=44. This is mainly because of the initial pulse of productivity due to growth of agricultural crops, and from transfer of carbon during decomposition of unburned
growth of agricultural crops, and from transfer of carbon during decomposition of unburned charcoal (see Figure 10). According to Houghton et al., (1983), agricultural land-uses result in an initial transfer of 33% of vegetation carbon to the soil. The subsequent rapid decrease in soil carbon storage occurs as a result of the fast decrease in cultivation productivity and the absence of forest cover providing continuous carbon litter (Houghton, Skole and Lefkowitz, 1991). COLCARB estimates a 26% loss of soil carbon storage by year=78 (minimum soil carbon content reached), similar to values of 15-30% reported by Houghton, Skole and Lefkowitz (1991). After abandonment of agricultural land, soil starts to recover its initial carbon content under secondary forest growth. At the end of the simulation, soil carbon has reached 80% of its initial value.

During the period of intensive agriculture (scenario B), simulated soil carbon content increases by 35% at year 44, due to primarily two factors; first, the initial peak in agriculture NPP, and second, carbon transfer from decomposition of the unburned charcoal (see Figure 10). Without forest cover to preserve soil carbon reservoirs, as soon as cultivation NPP starts decreasing, so will soil carbon storage. When agricultural lands are abandoned and used for livestock grazing, soil carbon will continue decreasing, but at a much slower rate. Since pasture is burned annually, land will continue to degrade from year-to-year. After 50-years of pasture, soil will have lost a total of 36% of the initial forest soil content.

![Figure 10. Storage of carbon in soil for different land uses in Natural scenario, scenario A and Scenario B.](image)

**Litter carbon storage**

Litter carbon content simulated for the control scenario reaches an equilibrium value between 3.8-4.6 t C ha\(^{-1}\) year\(^{-1}\) (see Figure 11), which is in strong agreement with the value of 4.4 t ha\(^{-1}\) year\(^{-1}\) observed by Foley (1995).

Peak litter carbon simulated for scenarios A and B corresponds to the addition of carbon from unburned charcoal remaining after biomass burning. Charcoal and unburned logs were assumed to decompose under the same conditions as vegetation litter. After the initial peak in litter carbon storage, most of the charcoal and unburned biomass is decomposed during the first 4-years, thus litter carbon eventually begins to decrease. Once agriculture
replaces forest, crop litter layer will start to grow, but the response-curve still decreases due to decomposition of the remaining charcoal and to the low content of carbon in crop litterfall. In Scenario B, during the pasture and livestock grazing stage, the litter layer decreases to lower values than the crop litter layer due to the annual practice of burning pasture litter layers.

Figure 11. Litter carbon in Natural (control), scenario A and scenario B simulations by COLCARB.

**Relative soil and litter moisture**

Retention of soil moisture is a dynamic process which is primarily driven by climatic factors (Ward, 1967, p.132). A major hydrological consequence of deforestation is a decrease in soil moisture content (Poveda and Mesa, 1999). Relative soil moisture is defined as the ratio of actual water content to maximum water content capacity, and is expressed as m³ ha⁻¹/m³ ha⁻¹. Because COLCARB was simulated with the same precipitation data every year, values vary between the same values every year (i.e. between 0.35-0.39) (Figure 12). During the 5-year shifting cultivation period in scenario A, precipitation and reductions in evapotranspiration were assumed to both decrease by 30%, resulting in soil moisture content decreased by 10-12% (i.e.0.31-0.34). Evapotranspiration and soil moisture content in scenario B behave in a similar fashion as scenario A during the 40-year simulation of mature forest and also during the 10-year period of intensive agriculture (Figure 12).
evapotranspiration, which in turn result in reduced contributions to local precipitation and a 6-8% decrease in soil moisture content (i.e. 0.29-0.31). Decreases in soil moisture content will affect crop NPP. Although this is an important feedback, for simplification purposes COLCARB could not incorporate this relationship in the integration of water and carbon sub-models. Neglecting this important feedback may affect maximum and minimum values of soil and litter carbon, but it would likely not alter general trends in the system’s behavior.

![Soil moisture behavior in the three proposed scenarios.](image)

Figure 12. Soil moisture behavior in the three proposed scenarios.

There is little significant change between the behavior of litter moisture content within all three simulation scenarios (Figure 13). Due to the low maximum water-holding capacity of the litter layer, litter moisture content was not affected by changes in precipitation and evapotranspiration, as much as soil moisture content.
Figure 13. Litter moisture during Natural (control), scenario A and scenario B simulations.

Runoff

Caquetá River runoff data was used to compare runoff values simulated by COLCARB (Figure 14). As COLCARB simulations incorporate the same precipitation data every year, Figure 14 shows variations in runoff within a 1-year period. Major differences between real and simulated runoff can be explained in terms of COLCARB’s very simplified two-layer (soil and litter) hydrological submodel. More complicated hydrological models often contain at least six or more layers (Sellers, 1996). However, as the main purpose of this study was to show general trends as opposed to exact numbers, changes in simulated runoff did not significantly differ from those expected.

Simulated and Real runoff Vs Time

Figure 14. Real and simulated runoff under Natural (control) conditions.
Runoff response is affected by factors such as geology, soil characteristics, hydraulic geometry, relief, vegetation, total precipitation and seasonal distribution (Reading, Thompson and Millington, 1995, p.239). A decrease of the mean flow of the rivers is another possible consequence of deforestation (Poveda and Mesa, 1996). Runoff in COLCARB is mainly driven by changes in precipitation and evapotranspiration. COLCARB simulations of runoff are plotted in Figure 14 for the Natural Scenario, Scenario A and Scenario B.

For the Natural Scenario, COLCARB simulates the runoff response to precipitation and evapotranspiration conditions when the mature forest is present. Runoff simulation of mature forest in scenario A and B behaves in the same way as in the Natural scenario. The runoff curve for the natural scenario (Figure 14) shows the same seasonal behavior yearly during the whole simulation period because the same precipitation data have been used every year. During the 5-year shifting cultivation period in scenario A, runoff decreases by 22-24% as a response to the decrease in precipitation. Later, when the successional vegetation starts growing, runoff starts increasing due to the increase in precipitation. Once, the successional vegetation has reached its evapotranspiration maturity, and precipitation has reached the point it had when the mature forest was present, runoff behaves in the same way as in the Natural scenario. Runoff in scenario B during the agriculture period behaves in a similar form as scenario A during the 5-year period of shifting cultivation (Figure 14). When pasture replaces agricultural production, runoff is reduced to a greater extent (12-13%). This reduction is due to the greater decrease in evapotranspiration and precipitation when pasture is present.

Figure 15. Runoff for Natural (control), scenario A and scenario B simulations.
4.2 Model sensitivity analysis

(a) Temperature dependence of decomposition

The temperature regulating factor during litter and soil decomposition was considered to be constant and it was calculated with a temperature value of 27°C. Mean annual temperatures in the Colombian Amazon region are between 24-28°C (IDEAM, 1999b). Litter and soil decomposition temperature regulating factors were tested for temperatures values of 24, 25, 26, 27, and 28°C in the Natural (control) scenario in order to see the effects of different temperatures on the amount of soil and litter carbon and on the net emissions (see Figure 16).

Litter carbon is little affected by changing temperature as seen in figure 16. Litter carbon content varies between 90-100% of the control simulated value. Net carbon emissions stabilize at different values for different temperatures. However, after stabilization, the pattern of the curve continues being flat, showing the balance between carbon uptakes and releases. Soil carbon is then the only variable a little bit more affected when changing the temperature. Soil carbon contents ranging from 80-100% of the control value are obtained after stabilization of the system. Neglecting temperature variations in litter and soil decomposition affects the accuracy of the results rather than affecting the expected trends.

Figure 16. Sensitivity analysis of net carbon emissions and soil and litter carbon for different temperature during soil and litter decomposition.
(b) Reductions in evapotranspiration and its consequent reduction in total precipitation

COLCARB reductions in evapotranspiration and precipitation in the hydrological submodel after removal of the forest are based on assumptions. Sensitivity of other assumed percentages of reductions is presented for scenario B in order to see the response of the system in soil and litter carbon, net carbon released to the atmosphere, soil and litter moisture, and runoff (See Figures 17 and 18). Since scenario B presents more land disturbances than scenario A, the former one was chosen for this part of the sensitivity analysis. Table 6 presents different reductions in evapotranspiration and total precipitation assumed for the sensitivity analysis during the intensive agriculture and pasture periods of scenario B.

Table 6. Assumed reductions in actual evapotranspiration (ET) and total precipitation (P) for the sensitivity analysis in scenario B.

<table>
<thead>
<tr>
<th>Period</th>
<th>Sensitivity experiment (1)*</th>
<th>Sensitivity experiment (2)</th>
<th>Sensitivity experiment (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>25 **</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Pasture and livestock grazing</td>
<td>35 ***</td>
<td>40</td>
<td>50</td>
</tr>
</tbody>
</table>

* Scenario B core values used for simulations. ** sensitivity experiment tested during the agriculture period with a 25% reduction in evapotranspiration and 25% reduction in total precipitation. *** Sensitivity experiment tested during the pasture and livestock grazing period with 35% reduction in evapotranspiration and 35% reduction in total precipitation.

Response of the system to the assumed condition 3 (see Table 6) presents higher reductions in soil moisture and runoff than the other 2 conditions as expected (see Table 7). Litter moisture is very little affected due to the low water holding capacities in the litter pool which makes this organic layer to saturate with little amounts of water. As a result of this dry condition, decomposition in the soil takes place at slower rates, being accumulated more carbon in the soil pools I in experiment (3) at the end of the simulation (81% of forest carbon content) than in the other two (72 and 64% for condition (2) and (1) respectively) and having lower rates of net carbon release to the atmosphere. This decrease in decomposition rates implies that carbon releases will prolong over time. Table 7 presents conditions 2 and 3 compared to condition (1) which is the selected condition during scenario B simulations.
Table 7. Conditions 2 and 3 compared to condition (1) for soil and litter carbon, net emissions, runoff and litter and soil moisture.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>% of reduction of condition (2) compared to condition (1)</th>
<th>% of reduction of condition (3) compared to condition (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon in litter</td>
<td>same as condition 1</td>
<td>same as condition 1</td>
</tr>
<tr>
<td>Net CO₂ emissions</td>
<td>3.2</td>
<td>7.4</td>
</tr>
<tr>
<td>Runoff</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>Relative litter moisture</td>
<td>4-5</td>
<td>4-8</td>
</tr>
<tr>
<td>Relative soil moisture</td>
<td>3</td>
<td>7-10</td>
</tr>
</tbody>
</table>

Figure 17. Response of soil and litter carbon contents and net emissions to the atmosphere to different reductions (conditions (1), (2) and (3) in table 3) in evapotranspiration (ET) and precipitation (P).
Figure 18. Response of soil and litter moisture and runoff to different reductions (conditions (1), (2) and (3) in table 3) in evapotranspiration (ET) and precipitation (P).

4.3 Implications for forest management and policies

Sustainable land-use can be one of the solutions to combat the consequences of deforestation and the subsequent land-use changes. For this, knowledge about water and carbon dynamics in forest ecosystems and their changes after land disturbances is crucial.

Even though COLCARB is a very simplified model that mainly simulates trends rather than providing very accurate figures, it illustrates some of the effects of deforestation and its subsequent land-use changes. Based on assumptions of decreases in total evapotranspiration and the subsequent after removal of the forest, the model responses at the hydrological level are mainly decreases in soil moisture and runoff. The simulated response of the carbon cycle due to deforestation and land-use changes includes large CO₂ emissions after burning and during the following years due to decomposition of the biomass left and loss of carbon from the soil and litter layers. Even though COLCARB does not model carbon sequestration by the successional vegetation when it is growing, it is possible to see increases in soil and litter carbon.

These trends can show policy-makers and forest managers what happens when the ecosystem is disturbed. These trends also show policy-makers the obvious need to invest into more detailed and deeper research about carbon and water dynamics in Colombian
tropical forest ecosystems in order to have a more real picture of the behavior of the ecosystem after land disturbances. Further improvements of COLCARB need to include energy balances, photosynthetic carbon uptake, more soil layers to get an accurate runoff, and important vegetation-atmosphere feedbacks.

Forest have the potential to increase or help to decrease the anthropogenic induced climate change through deforestation and land-use changes or through carbon sequestration during forest regrowth respectively. A complete understanding and measurement of carbon sequestration in Colombian rainforests could be a good option for Colombia to play an important role at the international level in the global warming mitigation opportunities created by the Kyoto protocol.

5. Conclusion

The modeling research presented in this thesis helps to illustrate general patterns of basic hydrological (i.e. runoff, litter and soil moisture content) and carbon (soil and litter carbon) behavior following deforestation and the transformation to two different land-use systems. Modeling data show conclusive evidence that deforestation followed by intensive agriculture (with subsequent pasture development) has long-term effects on net CO₂ emissions to the atmosphere. Alternatively, deforestation followed by less-intensive agricultural practices such as shifting cultivation (with subsequent secondary vegetation regrowth) has much shorter and less severe consequences for net CO₂ release to the atmosphere, because of carbon conservation induced by secondary forest regrowth. At the hydrological level, model responses to deforestation are decreases in soil moisture and runoff. Modeling trends, such as presented in this study, can be of significant use for policy-makers and forest managers in Colombia, because not only does it help to illustrate some of the general impacts of tropical deforestation and land-use systems on global CO₂ budgets, but it plays an even greater role in highlighting the need for more detailed and site-specific research addressing carbon and hydrological cycling in the Colombian Amazon rainforests.

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6. References


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Tobón M. C. PhD. University of Amsterdam. PhD thesis: Monitoring and modelling hydrological fluxes in support of nutrient cycling studies in Amazonian rain forest ecosystems. TEL +31 (0) 20 52 57 442. FAX +31 (0) 20 52 57 431. e-mail: C.Tobon@frw.uva.nl e-mail: ftropenb@trauco.colomsat.net.co Communication via e-mail. Part of the information used is unpublished information.
Appendix A

Scenario A data

Figure 19. NPP of agricultural species during the shifting cultivation period.

Increases in secondary forest NPP through time

Figure 20. Increases in secondary forest NPP though time.

Increases in evapotranspiration during the growth of the secondary forest

Figure 21. Increases of evapotranspiration with time during the growth of secondary forest.

Scenario B data

Figure 22. Crop NPP during the intensive agriculture period of scenario B.