Amazonian Deforestation and Climate

Edited by

J.H.C. GASH
Institute of Hydrology, UK

C.A. NOBRE
Centro de Provisão de Tempo e Estudos Climáticos, Brazil

J.M. ROBERTS
Institute of Hydrology, UK

R.L. VICTORIA
Centro de Energia Nuclear na Agricultura, Brazil

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22 Disturbance and recovery of tropical forests: balancing the carbon account

R.M. LUCAS[1], P.J. CURRAN[1], M. HONZAK[2], G.M. FOODY[2], I. do AMARAL[3] and S. AMARAL[4]
[1] *University of Southampton, UK*
[2] *University of Wales, Swansea, UK*
[3] *Instituto Nacional de Pesquisas da Amazônia, Manaus, Brazil*
[4] *Instituto Nacional de Pesquisas Espaciais,* São *Paulo, Brazil*

INTRODUCTION

The recent widespread conversion of mature tropical forests to agriculture and other land uses has resulted in a large reduction in biotic carbon reserves and contributed to 30% of the annual increase in atmospheric carbon dioxide (Bueno and Helene, 1991). Current estimates suggest that between 1.2 and 2.6 Pg of carbon is transferred to the atmosphere annually through worldwide conversion of tropical forests (Houghton *et al.*, 1990; Brown *et al.*, 1993; Sampson *et al.*, 1993; Dixon *et al.*, 1994). These losses of terrestrial carbon have, however, been partly offset by sequestration of atmospheric carbon by regenerating forests (Brown and Lugo, 1990).

An assessment of the carbon stocks of both mature and regenerating forests is required if changes in the carbon flux resulting from tropical land cover transformations are to be modelled (Curran *et al.*, 1996). Carbon stocks may be estimated from forest biomass by applying a conversion factor of approximately 0.5 (Atjay *et al.*, 1979; Iverson *et al.*, 1992; Brown *et al.*, 1993; Dixon *et al.*, 1994) and the biomass of forest stands may be established through, for example, destructive harvesting of trees or timber volume sampling (Brown and Iverson, 1992; Detwiler and Hall, 1988; Bueno and Helene, 1991; Houghton *et al.*, 1987). Estimates of the biomass of mature tropical forests are, however, scarce, and due to the spatial heterogeneity of these forests, are often unrepresentative of the forest as a whole (Brown and Iverson, 1992). As a result, there is considerable uncertainty as to the quantity of carbon held within mature closed forests and also in the proportion of this carbon that is released to the atmosphere through biomass burning and decomposition (Smith *et al.*, 1993; Sampson *et al.*, 1993). The fraction of this carbon restored to the terrestrial system by tropical regenerating forests is also unknown as few studies have assessed the rate and quantity of carbon uptake by these forests.

Models of tropical carbon flux require spatial estimates of the extent of both mature and regenerating forest. Several research groups have estimated the spatial extent of tropical closed forest for regions such as Amazonia (e.g. INPE, 1990; INPE, 1992;

Amazonian deforestation and climate. Edited by J.H.C. Gash, C.A. Nobre, J.M. Roberts and R.L. Victoria.

Joint Research Centre, 1992; Skole and Tucker, 1993) by using remotely sensed data. However, up-to-date estimates of the regional extent of regenerating forests are generally unavailable due mainly to the rapidly changing nature of land cover in the tropics, although Brown and Lugo (1990) suggest that regenerating forests represent over 31% of the tropical closed forest area and are forming at a rate of 90×10^3 km^2 y^{-1}.

The larger expanses of regenerating forest in Brazilian Amazonia correspond closely to the areas of deforestation. The loss of mature forests in this region accelerated after the 1960s and, as a consequence, many of the regenerating forests are less than 30 years old and at a stage when the rate of carbon assimilation into the biomass is at a maximum (Brown and Lugo, 1990; Whitmore, 1990). These younger regenerating forests represent a significant sink for atmospheric carbon. The expansion and growth of these forests can be mapped using data from remote sensing satellites which have been observing the entire tropical belt for at least the past 20 years (Foody and Curran, 1994). Archives of Landsat MSS (Multi-spectral Scanning System) and TM (Thematic Mapper) data extend back to 1972 and 1982 respectively (Sader *et al.*, 1990) giving a unique record of land cover transformations (e.g. mature forest loss, agricultural expansion and regeneration) in the tropics.

A number of studies (Mausel *et al.*, 1993; Moran *et al.*, 1994) have involved the use of a time-sequence of remotely sensed data to describe the extent and succession of tropical regenerating forests. Time sequences have also been used to provide estimates of the age of regeneration. For example, a study undertaken at a site north of Manaus (2°20'S, 60°00'W) in the Brazilian state of Amazonas used a time-sequence of Landsat MSS/TM data to age forests regenerating on abandoned cattle pastures (Lucas *et al.*, 1993). However, for carbon flux models, different stages of forest regeneration need to be defined as a function of biomass, and hence carbon content. The research described in this chapter, which is an extension of the time series analysis undertaken by Lucas *et al.* (1993), aimed first to define several different stages of tropical forest regeneration at the Manaus site and then to map the extent of each stage using remotely sensed data. The ultimate aim of the research was to assign estimates of biomass to each of the regeneration stages defined and thereby generate spatial estimates of biomass and carbon.

FOREST LOSS AND REGENERATION ON CATTLE PASTURES

In Brazilian Amazonia, the 15 million hectares of cattle pasture (Smith *et al.*, 1995) represent approximately 65% of the estimated 23 million hectares of land that has been deforested (excluding fragmented forest: Skole and Tucker, 1993). The reductions in carbon stocks resulting from this land cover transformation are perhaps the most extreme, as most farms (or fazendas) were established on land covered previously with relatively undisturbed closed mature forest (Brown and Lugo, 1990).

The majority of the cattle pastures in Brazil were formed following the introduction of fiscal incentives in the late 1960s (Serrão *et al.*, 1978; Fearnside, 1988). These incentives were also largely responsible for the establishment of cattle ranches along the BR 174 Highway which was constructed in the early 1970s to connect Manaus with the Roraima state capital, Boa Vista. As with many of the pastures in Brazilian Amazonia, the withdrawal of tax incentives in the late 1980s and the general decline in land productivity through inadequate management strategies led to the widespread degradation and eventual abandonment of many fazendas near Manaus and this, in turn, provided sites for forest regeneration (Fearnside, 1988; Corves and Bax, 1992).

STUDY SITE

The main study sites were the BDFFP (Biological Dynamics of Forest Fragments Project) research area of the Brazilian National Institute for Amazonian Research (INPA) and the Smithsonian Institution, and regenerating forest blocks within the Reserva Ducke, which are both located to the north of Manaus (see Figure 1 of Honzak *et al.*, 1996). Before the field campaign, the approximate age of the regenerating forests at the BDFFP site (within Fazendas Porto Alegre, Esteio, Maringa and Agroman) was determined initially from a time-series of Landsat TM data for the years 1985, 1988, 1989 and 1991 (Lucas *et al.*, 1993) and then increased in accuracy by using Landsat MSS data from 1976-1984 and a SPOT HRV image from 1986. The ages of forests in the Reserva Ducke were determined from INPA records.

FIELD DATA COLLECTION

Inventory plots (10 × 100 m) were located within a range of regenerating forests of known age. Thirteen of the plots were located within forests at the BDFFP site (which ranged in age from 4 to 16 years) while a further two plots were located in the Reserva Ducke in stands aged at 21 and 30 years respectively. Within each plot, data were collected on tree diameter (for all trees greater than 3 cm in diameter) and species composition. A more detailed description of the field data collection is presented by Honzak *et al.* (1996).

CLASSIFICATION BASED ON FOREST INVENTORY DATA

To express the floristic composition of each plot, an Importance Value Index (IVI), which is a combined measure of the percentage relative frequency, abundance and dominance for each species or genus identified (Krebs, 1972), was calculated. Three types of forest regeneration at the study site were then classified according to the IVI recorded for genera within each plot (Table 1). In two plots, the IVI was greatest for species of the genera *Vismia* (>30%) and the combined IVI for the genera *Miconia*

Table 1 The major secondary forest types identified within the BDFFP site near Manaus

Forest type	Main genera	IVI
F_{VMB}	*Vismia*	> 30 %
	Miconia	> 8 %
	Bellucia	> 13 %
F_{CP}	*Cecropia*	> 39 %
F_{Mix}	*Cecropia*	> 20 % but < 39 %

and *Bellucia* (Family: *Melastomataceae*) exceeded 20%. In this study, these forests are referred to as F_{VMB}. In many plots, however, the pioneer tree genus *Cecropia* predominated (IVI >20 %). Within six plots, the IVI for *Cecropia* exceeded 39 % and trees of this genus formed an umbrella over an understorey comprised mainly of species of the genera *Aparisthmium*, *Inga*, *Pourouma*, *Guatteria*, *Laetia* and *Byrsonima*. Within three plots, the IVI for *Cecropia* ranged between 20-30%, although the umbrella of *Cecropia* was either penetrated by other fast growing genera (e.g. *Goupia*) or experienced natural dieback and thereby exposed an understorey of other secondary forest species (e.g. *Laetia*, *Goupia* and *Miconia*).

Consequently, where the IVI for *Cecropia* exceeded 39%, forests were classified as F_{CP}, whilst remaining forests, which represented the changeover from early pioneer to slower growing secondary and primary forest species and therefore a later stage of forest regeneration, were classified as F_{Mix}. The forests sampled within the remaining two plots at the BDFFP site contained a large number of genera although the IVI of few exceeded 10 %. These forests were classified as F_{Mix} as their overall species composition was typical of this forest type. The two forests sampled at the Reserva Ducke were considered to be a later successional stage of F_{Mix}.

CLASSIFICATION USING REMOTELY SENSED DATA

Following the definition of regenerating forest types on the basis of the IVI, the potential for estimating the spatial extent of each type using remotely sensed data, either singly or in a time-series, was assessed.

SPECTRAL SEPARABILITY OF FOREST TYPES

As an initial step to the classification of a single-date Landsat TM image (8 August, 1991) of the BDFFP site, image statistics relating to each of the three forest types were obtained by identifying image pixel coordinates which corresponded to the field coordinates of the plot locations (determined using a Magellan Global Positioning System NAV 5000 PRO). The spectral separability of the three successional forest types within TM Channels 3 (visible), 4 (near-infrared) and 5 (mid-infrared) was then assessed on the basis of a transformed divergence algorithm which provided a measure of the statistical separation of pairs of classes as a covariance-weighted distance of between-class means (Singh, 1984). This analysis suggested that forest types F_{VMB}, F_{CP} and F_{Mix} were spectrally indistinguishable from mature forest in the visible channels but separable from mature forest in the near and mid-infrared channels. A feature space plot of the near and mid-infrared wavebands (Figure 1) also demonstrated that as regenerating forests colonised pasture, the near and mid-infrared radiance of both F_{CP} and F_{VMB} first increased to a maximum (due perhaps to increases in leaf cover) and thereafter declined steadily (due to increased shadowing) and eventually merged with that of mature forest. The analysis also illustrated a greater similarity in the near and mid-infrared radiance of both F_{VMB} and F_{Mix} to mature forest, compared to that of F_{CP}. This may be a function of the smaller leaf size and more vertical orientation of leaves within the upper canopy of both the mature forest and F_{VMB}/F_{Mix} compared to the larger leaf size (often >1 m) and more horizontal leaf orientation characteristic of the upper canopy of F_{CP}.

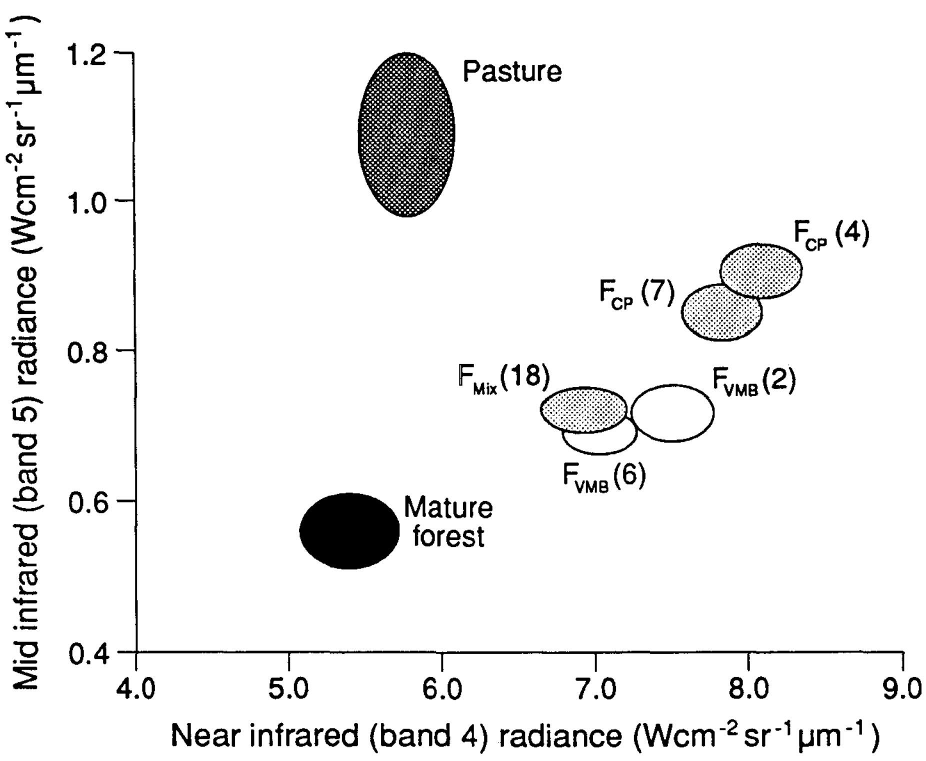


Figure 1 Near and middle infrared response of different stages of forest regeneration, mature primary forest and pasture at Manaus, as defined using the Landsat TM. Figures in brackets represent the forest age in years.

CLASSIFICATION OF F_{CP} USING SINGLE-DATE LANDSAT TM DATA

The pattern of spectral signatures for the different regenerating forest types within the feature space plot of Landsat TM Channels 4 and 5 suggested that their discrimination within the image may be achieved through classification. A texture-based maximum likelihood classification algorithm based on a causal Markov random field model (Palubinskas, 1988) was therefore applied to Channels 3, 4 and 5 of the 1991 Landsat TM image. Based on the knowledge obtained through both field inventories and observations, training statistics were derived (from raw data values) for 11 land cover classes, including the three forest regeneration types, and used in the classification (Foody *et al.*, 1996).

To test the accuracy of the classification, further sites representing each of the 11 land cover classes defined were identified within the image, and the accuracy of their classification was expressed as a percent correct allocation. The overall percent correct allocation for the 11 classes, was 86.5 %, while unweighted and weighted kappa coefficients were 0.83 and 0.93 respectively. These accuracies were consistently larger compared to conventional per-pixel maximum likelihood and minimum distance algorithms performed on the same data set (Foody *et al.*, 1996). However, the classification was unable to provide a reliable discrimination of F_{VMB} from F_{Mix} although the separation of F_{CP} from both F_{VMB} and F_{Mix} was achieved on the basis of textural and spectral measures alone. Additional sources of data which could be used to discriminate F_{VMB} and F_{Mix} within Landsat TM imagery were therefore investigated.

DISCRIMINATION OF F_{Mix} FROM F_{VMB}

Previous studies on forest regeneration in Amazonia indicated that *Cecropia* and *Vismia* species are widespread throughout the region (Richards, 1952; Fearnside, 1988; Whitmore, 1990), with the former commonly occupying agricultural sites abandoned within several years of initial forest clearance, and the latter favouring the more intensively used lands (Uhl *et al.*, 1981; Uhl and Jordan, 1984; Uhl *et al.*, 1988; Buschbacher *et al.*, 1988).

The intensity of land management is partly a function of the period of land occupation. The length of time pastures were used at the BDFFP site before abandonment was therefore determined by tracing land use within a time-sequence of Landsat MSS/TM and SPOT HRV imagery recorded between the early 1970s and 1991. This analysis indicated that the majority of pastures which were abandoned within 1-3 years of clearance corresponded to the areas classified as F_{CP} by Foody *et al.* (1996). It was therefore assumed that F_{Mix}, being a more advanced successional stage of F_{CP}, would also only occupy land abandoned within the first three years of clearance, whilst F_{VMB} would dominate areas used for longer periods. On this basis, F_{VMB} and F_{Mix} were distinguished and all forest types were subsequently aged using the time-sequence of remotely sensed data. In the final classification, 11 classes representing three forest types of different age were mapped for the BDFFP site alone (Figure 2).

ESTIMATION OF BIOMASS AND CARBON STOCK

The total biomass was estimated for each of the fifteen plots by using allometric regressions derived by Deans *et al.* (1996). These regressions were generated by destructively harvesting and weighing the above and below-ground components of six *Terminalia*, four *Trema*, three *Musanga* and one *Triplochiton* tree (with diameters ranging from <5 to 20 cm) which are regenerating forest species native to West Africa (Honzak *et al.*, 1996). The regressions estimate total biomass as a function of diameter at breast height (D, cm) and total height (H, m) with or without wood density (S, Mg m^{-3}). The values of S were taken from Reyes *et al.* (1992) and H was estimated from D by using the regression defined by Brown *et al.* (1989) for forests located within the tropical moist life zone (Honzak *et al.*, 1996).

To scale-up plot biomass to the larger areas of forest, the estimates obtained from the thirteen plots at the BDFFP site were assumed, on the basis of plot location alone, to indicate the biomass associated with seven of the eleven forest classes defined in Figure 2. The biomass of the five unsampled forest classes was estimated from regressions relating forest age to biomass as defined (for the inventoried forests) using the allometric regressions of Deans (1996). The appropriate biomass estimates for all 11 forest classes were then scaled-up to the area of each forest class to generate spatial estimates of biomass for all regenerating forests at the BDFFP site (Figure 3). The carbon associated with each regeneration stage was then approximated by assuming carbon stocks to be half of the biomass (Iverson *et al.*, 1994).

The estimates of carbon for each stage of regeneration can be aggregated to assess the magnitude of the carbon sink associated with all regenerating forests at the BDFFP site. Similarly, both carbon stocks held within the undisturbed mature forests and the losses of carbon resulting from the conversion of these forests to pasture can be approximated on the basis of published estimates of mature forest biomass (e.g. McWilliam *et al.*, 1993). By using these spatial estimates of carbon, the fluxes of carbon associated with tropical deforestation and regeneration can be modelled.

BALANCING THE CARBON ACCOUNT

In the simplest terms, the release of terrestrial carbon associated with the conversion of mature forests to agriculture can be quantified as a product of the carbon per unit area of forest and the total area of forest loss. However, the complexity and spatial variability of the structure of mature tropical forests, which results partly from the large diversity and partly from a dynamic natural succession, has prevented the assignment of a value or range of values which accurately define their biomass. For example, estimates of total above-ground biomass for moist closed forests near Manaus range from 275 Mg ha^{-1} (Rodrigues, 1967) to 563 Mg ha^{-1} (Lechthaler, 1956; Figure 4). This large variation in estimated biomass for mature forests is due mainly to differences in both the location of inventories and sampling methodologies (Brown and Iverson, 1992). The biomass estimate of Lechthaler (1956) at the

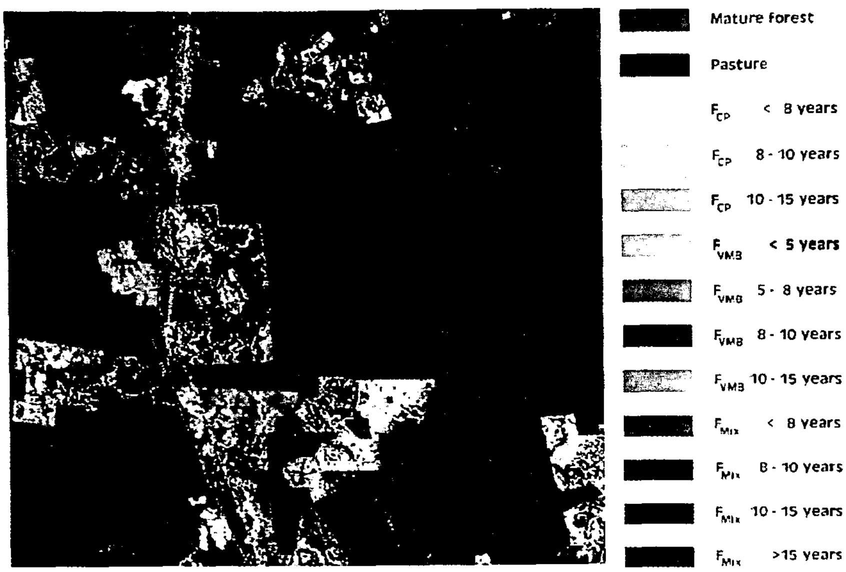


Figure 2 The classification of regenerating forest types at Manaus. F_{CP} was discriminated from other forest types on the basis of spectral and textural differences in Landsat TM Channels 3, 4 and 5. A time sequence of Landsat TM imagery was analysed to define both land management history, which was used subsequently to distinguish F_{VMB} and F_{Mix}, and the age of regrowth.

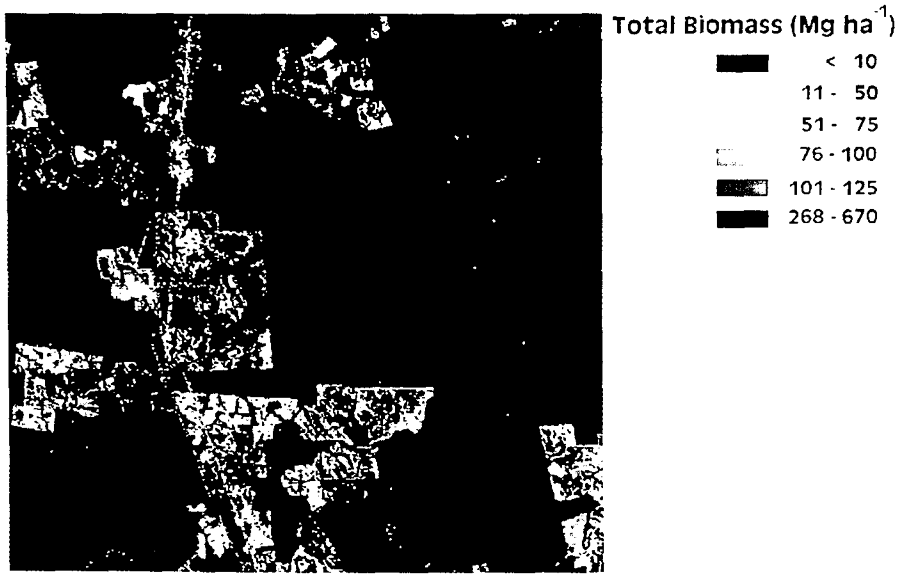
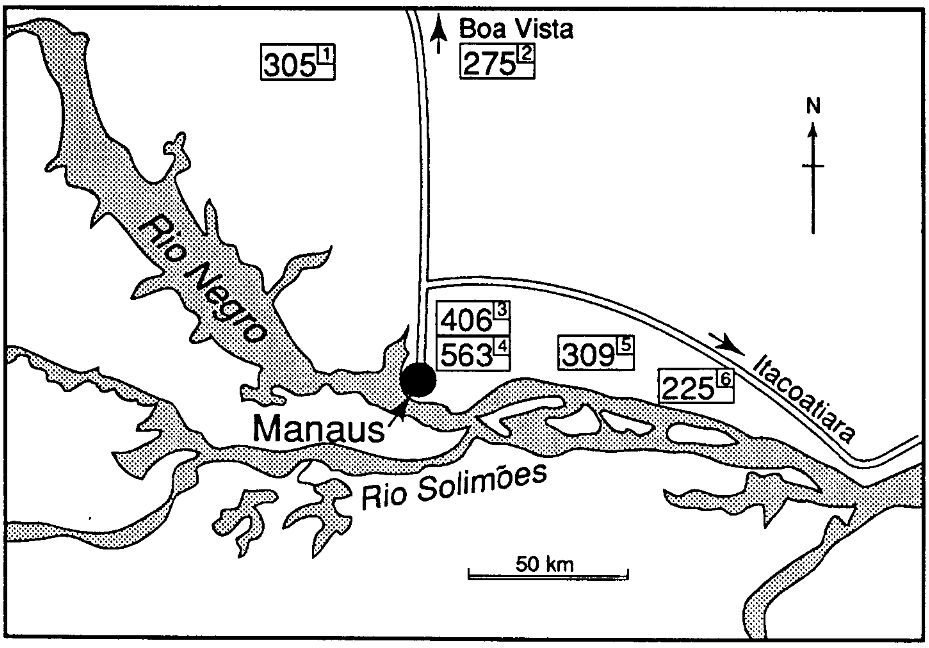


Figure 3 Estimates of total biomass stocks associated with regenerating forests at the BDFFP site, Manaus, as defined using the allometric regressions of Deans *et al.* (1996) and the height estimation equation of Brown *et al.* (1989).

Reserva Ducke, for example, is one of the largest recorded for mature Amazonian forests and may be biased due to the inclusion of big trees within the sample or the selection of an unrepresentative plot (Brown and Iverson, 1992). The wide range of biomass estimates for mature forests near Manaus therefore prevents an accurate assessment of the carbon stocks associated with mature forests and the carbon losses resulting from the conversion of these forests to cattle pasture and agricultural lands. Furthermore, there are considerable uncertainties in the quantity of below ground biomass of mature forests and the fluxes of carbon resulting from the decomposition of this component following forest removal. The rate of carbon release to the atmosphere during the conversion process is also variable with large and immediate losses resulting from biomass burning and more gradual releases occurring during long-term decomposition (Fearnside, 1985).

Because of the uncertainties in the carbon stocks of mature forests, the time-period required for regenerating forests to recover carbon to pre-disturbance levels is unknown. However, one approach used to estimate the time period required for



1 Forest managment basin 90 km N of Manaus (Higuchi *et al.*, 1985)
2 Km 42 Boa Vista Rd. (McWilliam *et al.*, 1993)
3 Adjacent to Walter Egler Forest Reserve (Klinge *et al.*, 1975)
4 Ducke Forest Reserve (Lechthaler, 1956)
5 Km 30, Itacoatiara Rd. (Prance *et al.*, 1976)
6 Km 64 - 200, Itacoatiara Rd. (Rodrigues, 1967)

Figure 4 Estimates of total above-ground biomass for mature primary forests at Manaus (Mg ha^{-1}).

complete carbon restoration at Manaus was to compare the range of biomass estimates obtained for mature forests with those derived for regenerating forests of known age. Within the 30-year old forest plot at the Reserva Ducke, for example, the total above ground biomass estimated using the allometric regressions of Deans *et al.* (1996) was 175 Mg ha^{-1}. By assuming that the total above ground biomass estimate of 275 Mg ha^{-1} (McWilliam *et al.*, 1993) is typical for mature forest at Manaus and that a linear rate of biomass accumulation is maintained, regenerating forests may potentially restore biomass (and hence carbon) to pre-disturbance levels within 50 years. However, the period required for forests to recover their pre-disturbance carbon stocks is extended considerably if the mature forest biomass estimate of 563 Mg ha^{-1} is considered true, particularly as the rate of biomass accumulation for regenerating forests declines after 30 years (Uhl, 1987; Saldarriaga *et al.*, 1988; Brown and Lugo, 1990).

DISCUSSION

The contribution of tropical regenerating forests to the reduction of carbon dioxide levels in the atmosphere is uncertain because knowledge of the biomass accumulated within different stages of forest regeneration is limited and there is little information on the spatial extent of each stage at both a local and regional level. This study has defined a methodology for estimating the age and extent of several types of forest regeneration by using remotely sensed data and suggested procedures for assigning biomass values to each of these forest types. Estimates of the biomass (and hence carbon stocks) associated with all regenerating forests at Manaus have been made. However, the errors associated with the classification of forest regeneration types and the estimation of biomass are likely to be large. The aim of this discussion is to provide an understanding of the main reasons for these errors.

CLASSIFICATION USING REMOTELY-SENSED DATA

Time sequences of remotely sensed data provide a unique insight into the dynamics of forest regeneration and agricultural land use in the tropics. This record of land transformation is, however, often incomplete because remotely sensed data may be unavailable for periods of up to several years. Changes in land cover may therefore remain undetected and the accuracy of estimates of forest age or periods of land use is also reduced. Even so, remotely sensed data often represent the only information source available for land cover mapping and monitoring, especially in areas undergoing rapid changes in land use.

In the analysis of time-sequences of remotely sensed data, the errors of class assignment associated with the classification of single date imagery and their subsequent comparison are compounded. This aggregation of errors is one of the main limitations of a stratified approach to the classification of land covers. In this study, additional errors were also introduced by superimposing the two-tiered classification of F_{CP}, F_{Mix} and F_{VMB} onto the age class map. In particular, the discrimination of F_{VMB} and F_{Mix} was based entirely on the assumption that the period of land use prior to abandonment was significant in determining the species composition of the regenerating forests. To a certain extent, this assumption was justified on the basis of previous studies of the species composition of forests regenerating on abandoned pastures (e.g. Uhl *et al.*, 1988) and also on the observed correspondence of the area occupied by F_{CP} (as determined from the texture-based maximum likelihood classification of Landsat TM data) and the land used for periods of less than three years. However, this assumption introduces the greatest uncertainty into the classification of regenerating forest types.

DEFINITION OF REGENERATION STAGES FROM FIELD DATA

The classification of F_{CP}, F_{VMB} and F_{Mix} using remotely sensed data also assumes that only these three distinct forest types existed at the BDFFP site. However, it is likely that a more mixed community of forests became established on many pastures. During the field campaign, only seven different forests, which colonised pastures abandoned either within 1-3 years of clearance or after five years of clearance were sampled. The classification of forest types therefore did not account for forests which occupied land used for 3-5 years and which may have been comprised of a mix of F_{CP} and F_{VMB} or were dominated by other pioneer genera. The classification of F_{Mix} from field data also assumes that these forests were originally of type F_{CP} whereas the only evidence for this was the large IVI recorded for *Cecropia* compared to other secondary forest species or observations of dieback of this genus within the forests sampled.

ESTIMATION OF THE BIOMASS OF REGENERATING FORESTS

The procedure for scaling-up biomass estimates from plots to the area of the forest assumes that forests of the same age and with similar histories of land management will support the same levels of biomass. Evidence for the homogeneity of these regenerating forests was obtained by comparing species data from five plots located within nine year old forest F_{CP} at Fazenda Porto Alegre. These forests were established on land cleared of mature forest in 1983 and abandoned in the same year. The comparison revealed that within all five plots, the IVI exceeded 39% for trees of the genus *Cecropia* and was similar for understorey genera. The similarity of the IVI for three of these plots is illustrated in Figure 5. Furthermore, the estimates of total biomass for the five plots, derived using the allometric regressions of Deans *et al.* (1996), ranged from 97 to 119 Mg ha^{-1}, which were similar to the 82 to 103 Mg ha^{-1} range obtained using the same allometric regressions for three plots within nine-year-old regenerating forest (F_{Mix}) at Fazenda Esteio.

The forests at Fazendas Porto Alegre and Esteio colonised land which was not used intensively prior to abandonment, and the entire pasture was abandoned at one time. The scaling-up procedure may not, however, apply so well to forests regener-

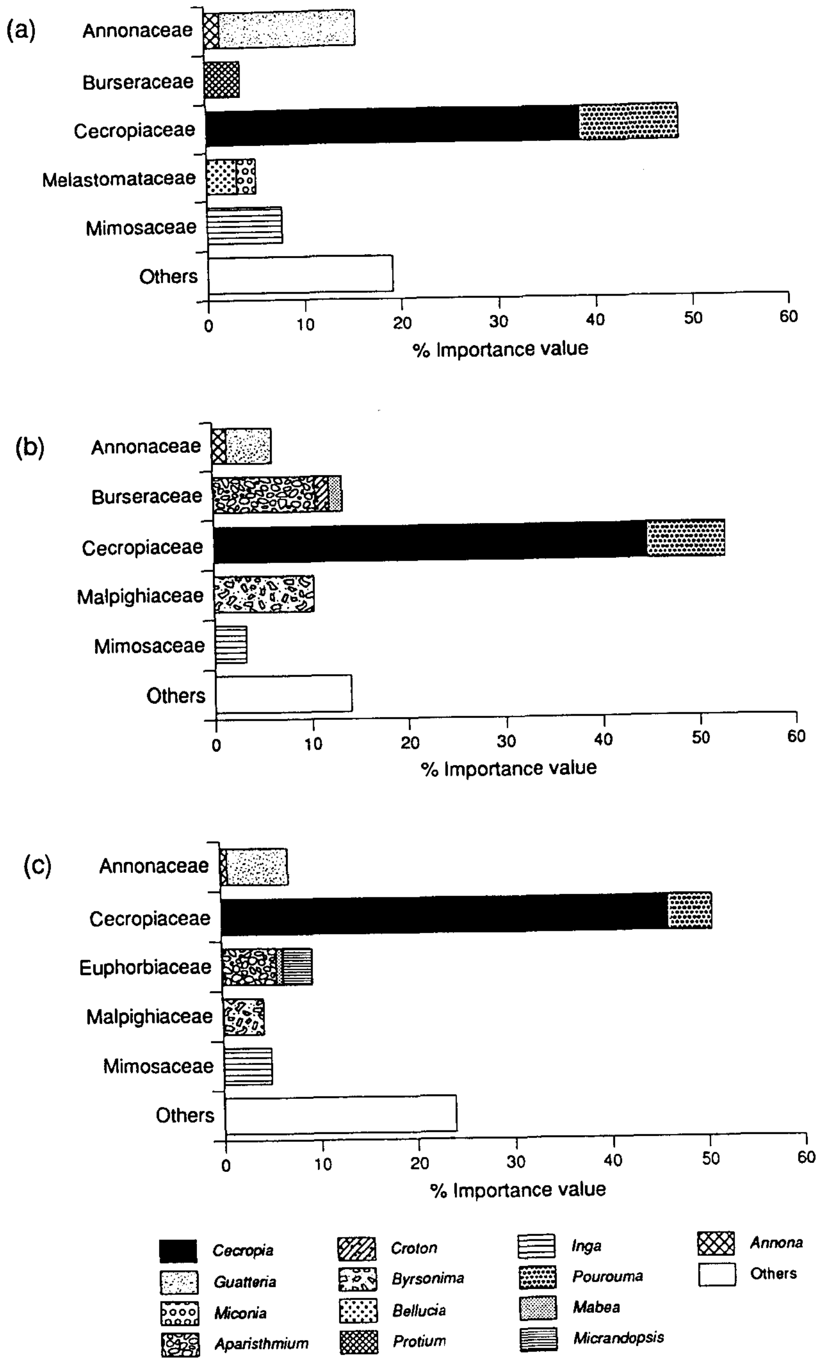


Figure 5 The similarity in percentage IVI of tree genera within (a) Plot 3, (b) Plot 4 and (c) Plot 5 in 9-year-old forest at Fazenda Porto Alegre demonstrates the homogeneity of regenerating forests establishing on many abandoned pastures. This forest colonised a pasture which was cleared of primary forest without the use of fire and was abandoned within a year of formation.

ating on sites which were used intensively for many years. For example, a comparison of the regenerating forest area within the time-sequence of remotely sensed data at Manaus indicated that the invasion of forests onto the more degraded pastures was gradual and often initiated from the boundary with the mature forests. The more random nature and timing of forest regeneration on these more intensively used pastures suggests that the structural and floristic homogeneity of these forests (e.g. F_{VMB}) is likely to be reduced compared to forests colonising less intensively used pastures (e.g. F_{CP}). Furthermore, the heterogeneity of all forest types is likely to increase with age as the dominance by a few pioneer genera is reduced through the influx of late regeneration and mature forest species. The species composition and growth of forests is also likely to vary according to factors such as soil type and topography. The procedure for scaling-up plot biomass estimates to the forest level should therefore be applied with caution.

CONCLUSION

This study has demonstrated the benefits, and also the limitations, of integrating remotely sensed data with forest inventory data to describe tropical forest regeneration on abandoned pastures and agricultural lands. In particular, time sequences of Landsat MSS/TM and SPOT HRV data can be used to map and describe in detail the expansion and utilisation of the deforested area and the regeneration of forests.

The analysis of field data suggested that three types of forest regeneration (F_{CP}, F_{Mix} and F_{VMB}) were common to the study site and that the composition of these forests was partly influenced by the history of land usage with F_{CP} colonising pastures abandoned within several years of clearance and F_{VMB} establishing on the more intensively used pastures. Furthermore, the study demonstrated that relatively homogenous tracts of forests may establish, particularly when entire pastures are abandoned shortly after clearance. The apparent homogeneity of forests of the same age and establishing themselves on land with a similar history of land usage provided the basis for scaling-up biomass estimates from plots to the area of the forest.

The estimates derived using the regressions of Deans*et al.* (1996) were considered, on the basis of previous studies (Uhl and Jordan, 1984; Uhl *et al.*, 1988), to be representative of the biomass of regenerating forests at Manaus and were therefore used to quantify carbon stocks within all regenerating forests at the BDFFP site. This analysis concluded that at least 50 years are required for regenerating forests to restore biomass and carbon stocks to pre-disturbance levels.

As carbon is released to the atmosphere through burning of fossil fuels and the removal of the world's forests, so there is compensation through the recovery of carbon by regenerating forests, enhanced levels of photosynthesis and carbon uptake and expansion of the forested area. Although the magnitude of this compensation is uncertain, remotely sensed data provide a tool for determining baseline information on the incremental growth of regenerating vegetation, the areas of forest loss and the extent of the remaining mature forest cover. Increasingly, more accurate plot biomass data and actual measurements of carbon flux are becoming available and these can be used in the future to provide a better understanding of the transfer of carbon between the terrestrial system and the atmosphere.

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RESUMO

A perda de carbono terrestre devido à conversão de florestas tropicais maduras para outros tipos de cobertura vegetal é parcialmente recuperada pela regeneração de florestas. Os fluxos de carbono associados à transformação da cobertura tropical, entretanto, não estão bem definidos devido à grande variabilidade das estimativas de carbono para florestas maduras e não maduras e devido ao conhecimento limitado da extensão espacial dessas florestas.

As perdas de carbono terrestre são especialmente grandes onde florestas maduras são substituídas por pastagens. Na Amazônia brasileira, as pastagens representam cerca de um terço da área desmatada, embora muitas tenham sido abandonadas e colonizadas por florestas em regeneração. Neste estudo, descrevemos alguns tipos de florestas em regeneração sobre pastagens abandonadas e terras cultivadas próximas a Manaus, e estimamos, utilizando uma série temporal dos dados do Landsat MSS/TM e SPOT HRV, a extensão espacial e a idade de cada tipo de floresta. Para cada tipo de floresta, a biomassa e o estoque de carbono foram estimados e mapeados. O estudo demonstra de que modo dados obtidos através de satélites de sensoriamento remoto e inventários sobre as florestas podem ser integrados a fim de estimar os fluxos de carbono associados à perda e subsequente regeneração de florestas tropicais.