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**PRODUTIVIDADE DE FLORESTAS NUM GRADIENTE
HÍDRICO NO INTERFLÚVIO PURÚS-MADEIRA**

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Manaus, Amazonas
Novembro, 2012

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**PRODUTIVIDADE DE FLORESTAS NUM GRADIENTE HÍDRICO NO INTERFLÚVIO
PURÚS-MADEIRA**

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Sinopse:

Foram estimadas a biomassa total acima do solo, estoque de carbono na biomassa, produtividade total acima do solo e sequestro de carbono na biomassa, e relacionadas com fatores hidrológicos e de estrutura do solo. Para todas estas estimativas foram utilizados dois modelos alométricos com três parâmetros. A partir dos resultados a área de estudo foi comparada com áreas inundáveis e de terra firme em outras regiões da Amazônia e considerações foram feitas a respeito de conservação e manejo florestal.

Palavras chave: Anéis de crescimento, Sequestro de carbono, Solos, Biomassa.

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Resumo

A crescente demanda por informações sobre produtividade florestal levou nos últimos anos a um aumento no número de parcelas permanentes estabelecidas na Amazônia. Entretanto, apesar deste esforço, a diversidade dos ambientes da região ainda não está suficientemente abrangida. Neste estudo a produtividade das florestas foi estimada e relacionada com fatores hídricos e edáficos em 8 parcelas permanentes distribuídas ao longo de 600 km no interflúvio Purús-Madeira. As estimativas foram realizadas pela combinação de dados de análises de anéis de crescimento da madeira com equações alométricas de estimativa de biomassa lenhosa. O valor médio de produtividade estimado foi $5,6 \pm 1,1 \text{ Mg ha}^{-1} \text{ ano}^{-1}$. A idade estimada das árvores teve forte relação com o diâmetro, e o incremento médio em diâmetro da parcela teve forte relação com a densidade média da madeira. Foi encontrada uma (a) relação positiva entre a produtividade da biomassa lenhosa e a condição de saturação de água do solo; (b) uma correlação negativa entre a produtividade e o teor de ferro nas camadas superficiais do solo e (c) uma relação negativa entre a idade média das árvores e as condições de saturação d'água do solo. Três hipóteses foram levantadas para esses resultados: (1) os solos mais saturados apresentam camada de plintita onde ocorre redução do ferro e liberação de fósforo para as plantas aumentando a produtividade; (2) o gradiente de saturação e a má estrutura do solo selecionam espécies adaptadas com maior produtividade e com ciclos de vida mais curtos e (3) árvores de ambientes saturados de água são favorecidas durante a estação seca, tendo fase de crescimento mais longa.

Abstract

Productivity of forests along a hydrological gradient on the interfluvial area between the Purus and Madeira Rivers, Amazonas, Brasil

The ongoing demand for information of forest productivity has increased the number of permanent monitoring plots across the Amazon. Those plots, however, do not comprise the whole diversity of forest types in the Amazon. In this study we estimate wood biomass productivity was estimated and related to hydrological and edaphic conditions. Forest productivity was estimated by a combination of tree-ring data and allometric equations for biomass estimation for eight plots distributed along 600 km on the Purus-Madeira interfluvial area that is crossed by the BR-319 highway, and related to hydrological and edaphic conditions. Estimated mean productivity was $5.6 \pm 1.1 \text{ Mgha}^{-1}\text{year}^{-1}$. There was a strong relationship between tree age and diameter, as well as between mean diameter increment and mean wood density of the plot. Wood biomass productivity was positively related to soil water saturation and negatively related to the iron content on the shallow surface of the soil. Also, the mean plot age was negatively related to the soil water saturation condition. Three hypotheses were raised to explain these results: (1) the reduction of iron molecules on the saturated soils with plinthite layers close to the surface leaves available phosphorous for the plants; (2) the poor structure of the saturated soils creates an environmental filter selecting tree species of faster growth rates and shorter life spans and (3) the plants on saturated soil are favored during the dry season, by not having restrictions in soil water availability.

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1. Introdução

A crescente necessidade por informação sobre produtividade e biomassa florestal na Bacia Amazônica ocasionou o aumento de parcelas de monitoramento permanente nos últimos anos (Baker et al. 2004; Malhi et al. 2004, 2006; Saatchi et al. 2007), mas o número de parcelas ainda é pequeno em comparação à vasta área de floresta. Para algumas regiões quase nenhuma informação existe, como é o caso da região interfluvial entre os rios Purús e Madeira, que é o foco deste estudo. Além disso, a maioria dos estudos usam modelos alométricos que utilizam apenas um parâmetro, em geral o diâmetro, para transformar inventários florestais em estimativas de biomassa. Estas estimativas apresentam tendência de superestimar ou subestimar os estoques de biomassa devido a variações comuns em densidade da madeira e altura das árvores (Chave et al. 2004, 2005; Wittmann et al. 2006; Feldpausch et al. 2011; Schöngart et al. 2011) que raramente são consideradas em estimativas de biomassa (Chave et al. 2004). Estudos recentes mostram que estes parâmetros são importantes para indicar estimativas precisas e descrever padrões regionais de biomassa e produtividade (Chave et al. 2004, 2005; Schöngart et al. 2010, 2011; Feldpausch et al. 2012), que são fundamentais para o desenvolvimento sustentável da região e estratégias de REDD e REDD+ da Convenção das Nações Unidas sobre Mudança do Clima (United Nations Framework Convention on Climate Change) (Nogueira et al. 2008a).

Diversas estimativas de biomassa florestal têm sido realizadas na Amazônia. Malhi et al. (2006) realizaram estimativas de biomassa de diversas tipologias de florestas num total de 227 parcelas no âmbito da rede de monitoramento florestal RAINFOR e extrapolaram a estimativa para toda a Amazônia, indicando um estoque de carbono na biomassa acima do solo no valor de 93 ± 23 Pg C (Pg - Petagrama = 10^{15} gramas). Saatchi et al. (2007) fizeram previsões com base em mais de 500 parcelas amostradas, totalizando um valor acumulado de 86 ± 20 Pg C na biomassa viva acima do solo. Já Nogueira et al. (2008a), levando em conta o desmatamento ocorrido na Amazônia Legal desde 1976, encontrou os valores de 87,6 Pg C a bacia Amazônica, entretanto os autores utilizaram equações diferentes para áreas de floresta densa e de floresta aberta, o que reduziu as incertezas geradas pelo uso de apenas uma equação alométrica para diferentes regiões. Assim como nos trabalhos de Malhi et al. (2006), Saatchi et al. (2007) e Nogueira et al. (2008a) a maior parte das estimativas de biomassa realizada na Amazônia foi feita

em florestas de terra firme (Schöngart et al. 2010), ou com predominância de dados referentes a este tipo florestal, que têm sido extrapolados para toda a bacia Amazônica. Comparados aos estudos realizados em florestas de terra firme, poucas estimativas de biomassa foram realizadas em florestas das planícies inundáveis. Porém, cerca de 30% da Bacia Amazônica são classificados em diferentes tipologias de áreas úmidas como várzeas, igapós, baixios, campinas, campinaranas e interflúvios inundáveis (Junk et al. 2011), mas há poucos estudos estimando estoques e a produtividade de biomassa lenhosa nestes ambientes.

Estimativas de biomassa podem ser consideradas simples quando comparadas a estimativas de produtividade de biomassa. Apenas depois de muitos anos de monitoramento de incrementos em diâmetro em parcelas permanentes é que estimativas de produtividade em biomassa lenhosa são possíveis (Clark et al. 2001). Entretanto, os impactos severos causados pelas taxas atuais e previstas de desmatamento na Amazônia (Soares-Filho et al. 2006), como por exemplo, dentro do Programa de Aceleração do Crescimento, geram a necessidade de rápida avaliação do crescimento de árvores, produtividade e idade florestal para prover bancos de dados que gerem critérios para o desenvolvimento sustentável da região Amazônica. Uma ferramenta eficiente para determinar idade e taxas de crescimento, necessárias para estimar a produtividade florestal, é a análise de anéis de crescimento. Dados de anéis de crescimento têm sido aplicados com sucesso para estimar a produtividade florestal para diferentes tipos florestais na Bacia Amazônica (Schöngart 2003; Stadtler 2007; Oliveira 2010; Schöngart et al. 2010) e também em áreas úmidas do Pantanal (Schöngart et al. 2011).

A ciência com base em estudos de anéis de crescimento (dendrocronologia) foi restrita às regiões temperadas por muito tempo, pelo fato de se acreditar que árvores de florestas tropicais não formam anéis de crescimento, ou quando os formam, são indistintos (e.g. Whitmore 1998). Diferentemente de regiões temperadas, onde os anéis de crescimento são formados pela dormência cambial induzida pelas baixas temperaturas do inverno, em regiões tropicais a formação de anéis de crescimento pode ser induzida pelo alagamento periódico ou pela presença de uma estação seca bem definida (Worbes 1989). Em florestas alagáveis, o pulso de inundação monomodal previsível (Junk et al. 1989) gera alterações na disponibilidade de nutrientes, oxigênio e água, suportadas pelas plantas por meio de adaptações fenológicas, morfológicas e fisiológicas (Parolin et al. 2004). Como resultado final as árvores chegam a um estado de dormência cambial, no qual seu crescimento fica extremamente reduzido ou cessa (Schöngart et

al. 2002), ocorrendo a formação de anéis anuais de crescimento (Worbes 1999). Em florestas de terra firme anéis de crescimento anuais são formados pela presença de estações secas bem definidas, situação comum em grande parte dos trópicos, que leva à dormência cambial (Worbes 1995; Brienen & Zuidema 2005).

A existência de anéis de crescimento anuais em florestas tropicais já foi demonstrada a mais de um século em diversas regiões tropicais através de datação por isótopos estáveis e radioativos de carbono, feridas cambiais, medidas de atividade cambial e contagem direta de anéis de árvores de idade conhecida (sumário em Worbes 2002). A anatomia da madeira dos anéis de crescimento pode ser classificada em quatro tipos pela a anatomia da madeira: (1) variações intra-aneis da densidade da madeira com aumento da densidade da madeira perto do final da estação de crescimento, (2) faixas de parênquima marginal que limitam o anel de crescimento, (3) uma alternância entre fibras e faixas de parênquima com mais fibras no lenho inicial e mais parênquima no lenho tardio e (4) variações no tamanho dos vasos condutores (anel poroso).

Neste estudo estimamos produtividade na biomassa lenhosa acima do solo usando dois modelos alométricos com três parâmetros independentes (diâmetro, altura e densidade da madeira) e análise de anéis de crescimento para oito parcelas de 1 ha distribuídas ao longo de aproximadamente 600 km na região interfluvial entre os rios Purús e Madeira. Relacionamos produtividade florestal com variações na topografia, estrutura e drenagem do solo. Comparamos nossos resultados com outras estimativas realizadas em diferentes tipos florestais na bacia Amazônica e discutimos possíveis aplicações no contexto de conservação e manejo florestal.

2. Objetivos

2.1 Geral

O objetivo geral deste estudo consiste em responder à pergunta: como os fatores edáficos e hidrológicos influenciam a produtividade de biomassa lenhosa acima do solo?

2.2 Específicos

- Estimar a biomassa lenhosa seca acima do solo das florestas com diferentes níveis de encharcamento, aplicando modelos alométricos da literatura que transformam dados de inventários florestais em estimativas de biomassa lenhosa;

- Estimar a idade, taxas anuais de incremento radial e a densidade da madeira dos diferentes locais de estudo;

- Estimar o sequestro de carbono na biomassa lenhosa através dos incrementos radiais e modelos alométricos.

- Relacionar (1) a densidade da madeira, (2) as taxas de incremento radial, (3) a estrutura etária e (4) os estoques de carbono das florestas com a hidrologia e solo dos ambientes estudados.

Capítulo 1

B. B. Ladvocat, J. Schiatti, T. Emilio, D. Martins, G. Moulatlet, P. Souza, C. Levis, C.A. Quesada, and J. Schöngart: Productivity of aboveground coarse wood biomass and stand age related to soil hydrology of Amazonian forests in the Purus-Madeira interfluvial area, Manuscrito em preparação para *Biogeosciences*.

Productivity of aboveground coarse wood biomass and stand age related to soil hydrology of Amazonian forests in the Purus-Madeira interfluvial area

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Abstract

The ongoing demand for information of forest productivity has increased the number of permanent monitoring plots across the Amazon. Those plots, however, do not comprise the whole diversity of forest types in the Amazon. In this study we estimate wood biomass productivity was estimated and related to hydrological and edaphic conditions. Forest productivity was estimated by a combination of tree-ring data and allometric equations for biomass estimation for eight plots distributed along 600 km on the Purus-Madeira interfluvial area that is crossed by the BR-319 highway, and related to hydrological and edaphic conditions. Estimated mean productivity was $5.6 \pm 1.1 \text{ Mgha}^{-1}\text{year}^{-1}$. There was a strong relationship between tree age and diameter, as well as between mean diameter increment and mean wood density of the plot. Wood biomass productivity was positively related to soil water saturation and negatively related to the iron content on the shallow surface of the soil. Also, the mean plot age was negatively related to the soil water saturation condition. Three hypotheses were raised to explain these results: (1) the reduction of iron molecules on the saturated soils with plinthite layers close to the surface leaves available phosphorous for the plants; (2) the poor structure of the saturated soils creates an environmental filter selecting tree species of faster growth rates and shorter life spans and (3) the

plants on saturated soil are favored during the dry season, by not having restrictions in soil water availability.

1. Introduction

The knowledge on different aspects of forest productivity has become a major priority on the last decades, considering the diversity of forest types existing in the tropics (Liebermann & Marengo 200; Clark 2001). Global climate models indicate that climate change will have huge impacts on the carbon uptake by terrestrial landmasses, but the predictions until the end of this century vary considerably indicating carbon releases and uptakes depending on the applied model (Friedlingstein et al. 2006). Also for the Amazon region climate models indicate opposite impacts on C-stocks in vegetation and soils in the future (Dufresne et al. 2001; Cox et al. 2008). Therefore, the quantification of carbon stocks and sequestration by forest growth for different forest ecosystems and wetlands in the Amazon region is important to develop strategies to prevent carbon emissions by degradation and deforestation and the sustainable development considering conservation and sustainable forest management. The increased number of permanent plots in the recent years has contributed to improve knowledge on regional variation in forest productivity across the Amazon Basin (Baker et al. 2004; Malhi et al. 2004; Giardin et al. 2010). The use of adjusted allometric models (Chave et al. 2005; Feldpausch et al. 2012) contributed to more reliable estimates on biomass storage and productivity in Amazonian forests. However, the existing studies have not covered the diversity of forest ecosystems across the Amazonia, where wooded wetlands constitute about 30% of the total area (Junk et al. 2011). In addition, little is known about environmental factors such as soil conditions, climate and hydrology control of wood biomass productivity in these wetlands.

It has been shown that in *terra firme* forests, that are not seasonally flooded, forest productivity responded negatively to severe droughts such as in 2005 and 2010 (Phillips et al. 2009; Corlett et al. 2011; Lewis et al. 2011). In forests that area seasonally flooded by the main rivers (floodplain *várzeas* and *igapós*), on the other hand, an enhanced tree growth has been attributed to El Niño-induced droughts, since the flooded period in El Niño years is shorter than in wet years (Schöngart et al. 2004; Schöngart and Junk 2007). It is also known that variations in productivity related to soil fertility in both *terra firme* and floodplain forests (Malhi et al. 2004; Schöngart et

al. 2005) consequently results in different stand ages (Schöngart et al. 2010) and biomass stocks (Malhi et al. 2004, 2006). However, the complex effects of soil, climate and hydrology on the productivity of seasonally waterlogged interfluvial wetland forests are still poorly understood.

It must be considered that the Amazon basin will undergo a severe transition towards a disturbance-dominated regime, mostly due to changes in land-use and climate (Malhi et al. 2008; Cook et al. 2012; Davidson et al. 2012). Hence, the severe impacts caused by continuous deforestation and degradation in the Amazon Basin, for instance within the infrastructure program of the Brazilian Federal Government (*Plano de Aceleração de Crescimento- PAC*), generate demands of rapid assessment of information to generate databases that help discriminate areas for forest management and conservation, and therefore contribute for a sustainable development of the Amazon region. In this context, information on tree growth, tree ages and forest productivity are important key data to establish criteria to define areas of conservation priorities and sustainable policies for sustainable management. An example of this potential is the Normative Instruction no. 009 from the Sustainable Development and Environment Ministry of the Amazonas State (*Secretaria de Desenvolvimento Sustentável e Meio Ambiente do Estado do Amazonas*), that establishes minimum logging diameters and felling cycle for several species of *várzea* wetland forests based growth models developed by tree-ring analyses (GOL-concept) (Schöngart 2008).

The most common field method to estimate wood productivity in the tropics is monitoring tree growth. However, only after many years of repeated diameter measurements in permanent plots, the estimates of diameter increment rates are reliable (Clark et al. 2001). Alternatively to monitoring tree growth, tree-ring analysis has been applied for reliable estimates of tree ages and mean diameter growth rates which are necessary to estimate the woody biomass production. Recently, tree-ring data have successfully been used to estimate wood biomass productivity in different forest types where annual tree rings occur in the central Amazon Basin (Stadtler 2007; Oliveira 2010; Schöngart et al. 2010) and also in the Pantanal wetlands (Schöngart et al. 2011). In the Amazon, annual tree rings occur in the non-flooded *terra firme* forests as a consequence of the rainfall seasonality with one dry and one rainy season during a year (Vetter 1995; Worbes 1989,1999; Dünisch et al. 2003; Brienen and Zuidema 2005; Zuidema et al. 2012). The rainfall seasonality in large catchment areas of the Amazon River and its large tributaries results in a

monomodal flood-pulse also leading to the formation of annual tree ring in the wood of species in the floodplain forests (Worbes 1989; Schöngart et al. 2002, 2004, 2005).

In this study we use tree-ring analysis combined with two allometric models with three independent parameters (diameter, height and wood density) to estimate aboveground wood biomass productivity in eight 1-ha plots in an interfluvial region between the Purus and Madeira Rivers distributed over 600 km. Our objective was a rapid assessment of wood biomass productivity applying tree rings and allometric models, in an area where the restoration of the BR 319 between Manaus and Porto Velho, the capitals of the Amazonas and Rondonia states, respectively, may lead to rapid deforestation and degradation (Fearnside et al 2009; Laurance et al. 2001; Soares-Filho et al. 2006; Davidson et al. 2012). First, we estimate wood biomass stocks by diameter, tree height and wood density applying two allometric models. Second, we use tree-ring data to estimate stand age and to model changes in biomass stocks over time. We then relate productivity and stand age to soil and hydrology conditions of the studied sites. Finally, we compare our results with other estimates of wood biomass productivity from different forest types of the Amazon basin and discuss their application in the context of conservation and forest management.

2. Material and methods

2.1 Study region

The study was carried out in the interfluvial area of the Purus-Madeira Rivers in the Amazonas State, Brazil, that is intersected by the BR-319 highway from north-east to south-west (Fig. 1). The dominant vegetation type in the northern part of this region is dense lowland rainforests, while in the south a transition towards opened lowland rainforests occurs, probably caused by increasing rainfall seasonality (IBGE 1997).

The predominant soil type for the whole interfluvial region is Plinthosol/Gleysol (Martins et al. 2012). These soils have a firm plinthite layer that can change to hardpan if exposed to repeated wet and drying cycles (Quesada et al. 2011). The land relief is plain and presents only low variations of a few meters at the regional scale (Brasil, 1978). On a local scale, frequent

variations of the topography of a few meters create temporary pools on the lower and poorly drained areas during the rainy season (Rossetti et al. 2005). The duration and intensity of the rainy season varies strongly from north to south along the interfluvial area declining from 2800 to 2100 mm annual precipitation with increasing rainfall seasonality (ANA, 2011; Table 1).

As indicated by future scenarios (Laurance et al. 2001; Soares-Filho et al. 2006; Fearnside et al. 2009; Davidson et al. 2012) the interfluvial region between the Madeira and Purus rivers will suffer huge impacts as a consequence of paving the BR-319 highway and the human occupation following in the next decades. To avoid deforestation, several conservation units (Sustainable Development Reserves, Extractive Reserves, State Forests) have been established along the highway. However, long-term scientific data on floristic composition, forest structure and dynamic are essential as a decision tool for the sustainable development of the region, as criteria for discrimination between areas of strict conservation or management priorities. A set of 11 research modules of the PRONEX project “Rapid Assessment for Long Duration Ecological Projects” (RAPELD) were established along the Purus-Madeira interfluvial region, with an average spacing of 60 km, as part of the research modules network of the Research Program in Biodiversity (PPBio, <http://ppbio/inpa.gov.br/br319>).

2.2 Sampling design

In each of the 11 modules established along the interfluvial region of the Purus-Madeira rivers, ten 1-ha plots (250 x 40 m) were installed at every kilometer on two 5 km-long trails (Magnusson et al. 2005), totalizing 110 plots in the interfluvial region. Each plot followed an isocline, to minimize variation in the topography and soil conditions within a plot (Magnusson et al. 2005). For this study, we selected four of the 11 modules (Table 1). The average distance between the modules was 140-200 km, spanning approximately 600 km distance (Fig. 1). At each area, we selected two of the 10 permanent plots, one on the highest altitude (well drained) and the other plot on the lowest topography (poorly drained), using SRTM-DEM data (Shuttle Radar Thematic Mapper Digital Elevation Model) (USGS 2000; Farr et al. 2007).

2.3 Soil data

Soil samples were obtained at all plots at distances of 50 m along the central 250-m long transect, totalizing six samples per plot. At each point, soil samples of 30 cm depth were extracted with a corer labeled and kept in sealed plastic bags for 2-5 days. On arrival at the laboratory, the samples were air dried at ambient temperature. After drying, composite samples were prepared from all points, resulting in one sample per plot. Soil texture was then analyzed following standard protocol of total dispersion using sodium pyrophosphate to obtain clay, sand and silt percentages (EMBRAPA 1997). The soil chemical composition was also analyzed. Soil water saturation in each plot was scored, using the classification index of Quesada et al. (2010) (Table 2), using soil samples of 7 m depth collected by the HIDROVEG project and 2 m depth pit descriptions dug in modules M01, M05 and M08. Soil water saturation conditions classified by an index are based on the effective depth of the soil, hydrological properties and the presence of a plinthite layer. This index may be an important edaphic parameter as it appears to be related to aboveground necromass (Martins et al. 2012). For one plot (M05-TN(-)500) no data for the soil water saturation index was available. For two plots no data on soil fertility were available. All soil samples were collected in cooperation with the HIDROVEG project and analyzed at the Thematic Soils Laboratory of the National Institute for Amazon Research (INPA).

2.4 Topographical and hydrological conditions

Terrain hydrological conditions were estimated by using remote sensing and field data. The plots were preselected based on SRTM data, to select a wide range of topographies within and between the selected modules. Afterwards we applied the HAND model (height above the nearest drainage) that indicated the vertical distance of the plot from the nearest water-table as an indicator for the hydrological conditions (Rennó et al 2008). The HAND model, based on SRTM data, was calculated for all plots (G. Moulatlet, unpublished data). We also used the soil water saturation index (Table 2) as a robust indicator for the terrain's hydrological condition, to relate wood biomass productivity to soil hydrology. The difference between this index and the HAND data is that the HAND data describes hydrology based on topography, and therefore will be most

effective in terrains with pronounced topographical variations, since the level of the groundwater table may vary with the elevation depending on the soil conditions. The water saturation index, on the other hand, is based on soil features that were developed by long-term underground water fluctuations, such as the depth of the plinthite layer (see Quesada et al. 2010), and is therefore a more reliable indicator for variations in soil water saturation of the study sites. HAND data can be obtained with less effort than the soil water saturation index, however, they are less reliable in terrains with a smooth topography as it is the case of our study region.

2.5 Fieldmeasurements

The RAPELD program records all trees with diameter at breast height (DBH) above 30 cm in the installed 1-ha plots. Trees with a DBH of 10-30 cm are considered on two 10-m large stripes on both sides of the 250-m long transect in the middle of the plot (0.5 ha) (Magnusson et al. 2005). In this study, we considered all trees with DBH >30 cm of the forest inventory (Schietti et al. unpublished data) in order to obtain data on wood densities as well as to estimate tree ages and diameter increment rates for each tree by tree-ring analysis. A total of 554 trees were sampled in the eight plots, from which 22 trees were not considered due to very low distinction of the tree rings. Table 3 shows the number of sampled trees with DBH >30 cm in each plot. The sampling effort per plot was 47 to 87 trees with DBH >30 cm per hectare, corresponding to 53-96% of all trees of this diameter class. Further we sampled 30 randomly selected trees within the DBH classes 10-30 cm in each plot. Palm trees (Arecaceae) were not considered in this study.

The DBH of all trees was measured by a diameter tape. In case of buttresses, diameter was measured above them to avoid overestimates of basal area and wood biomass. Tree height was estimated using a height measurement device (Blume Leiss BL6). Two wood samples were extracted from the trunk of each tree using an increment borer of 5.15 mm inside diameter. The collecting of wood samples was made 10 cm below the DBH (120 cm above the forest floor) to avoid errors for future repeated diameter measurements with the aim to monitor forest dynamics. One sample was extracted for wood density determination. To avoid dehydration these samples were labeled with the plot and tree number and stored in closed plastic bags. The second sample was extracted to estimate diameter increment rates. These wood samples were glued on wooden

supports with identity numbers for plot and tree. All wood samples were transported to the Dendroecological Laboratory of the scientific cooperation between INPA and MPIC in Manaus (Max Planck Institute for Chemistry) for further analyses.

2.6 Botanical data:

All sampled individuals are currently being identified by Priscila Souza and Carolina Levis. The botanical material was pre-identified in field with the help of a parataxonomist. After a preliminary identification, the botanical identification was confirmed with the aid of specialists, identification guides and by comparing the vouchers collected to specimens at the INPA Herbarium (Manaus, Brazil) and virtual herbariums (<http://sciweb.nybg.org/science2/vii2.asp>). Fertile specimens will be deposited at INPA and sterile material will be stored in an adjacent working collection. Plants were identified in accordance with the APGIII (Angiosperm Phylogenetic Group III) classifications. For name correction of the taxa the Brazilian Flora Species List was consulted (<http://floradobrasil.jbrj.gov.br/2012/>).

2.7 Biomass and Carbon Stocks Estimates

Information on the sum of the basal area per hectare of all trees with DBH between 10 cm and 30 cm and information on those with DBH >30 cm which were not sampled were obtained from forest inventory data (J. Schiatti et al., unpublished data). Since trees with DBH of 10-30 cm are sampled only on 0.5 ha in the existing inventory, information on basal area for this cohort was multiplied by factor two to obtain estimates for the entire hectare.

To determine wood density (ρ) the fresh volume (V_{fresh}) of each sample was determined by the water displacement method. The wood sample was mounted on a needle and immersed into a recipient filled with water on an analytic balance calibrated to zero. The sample volume is equal to the indicated weight of the displaced water after placing the sample entirely into the water without touching the side or the bottom of the recipient. After this step of analysis the samples were dried at a temperature of 105°C to obtain their dry weight (W_{dry}) (Chave et al. 2005; Schöngart et al. 2005). Wood specific density was then calculated as:

$$\rho = W_{dry} / V_{fresh} \quad \text{Eq. (1)}$$

For each plot we calculated the mean wood density and standard deviation.

Since there are large distances between the four study areas and the vegetation type shift from the north to the south within the interfluvial region, possible differences in tree height and wood density between the areas can be expected (Chave et al. 2005; Wittmann et al. 2006; Nogueira et al. 2008a, b; Feldpausch et al. 2011). As there are no specific allometric models available for the studied forest types, two models from other biogeographic regions were used for estimates of aboveground wood biomass (AGWB) (Cannell 1984; Chave et al. 2005). These models use diameter, height and wood density as independent parameters to enhance the quality of the AGWB estimates (Chave et al. 2004, 2005; Schöngart et al. 2010, 2011) since the use of allometric equations with less than three independent parameters would lead to strong biases in the data (Feldpausch et al. 2012). For all of the equations described below, the parameters are referred as: aboveground coarse wood biomass (AGWB in kg), diameter at breast height (DBH in cm), tree height (H in m), and wood density (ρ in g cm^{-3}).

Cannell (1984) used a constant form factor ($F=0.06$) to estimate woody biomass for tree species from the pantropics as the following product:

$$\text{AGWB}_1 = \pi \cdot \left(\frac{\text{DBH}}{2}\right)^2 \cdot H \cdot \rho \cdot F \quad \text{Eq. (2)}$$

Chave et al. (2005) developed different allometric models for forests types submitted to different climate conditions. For lowland rainfall forests with a marked dry season of 1-4 months and 1500-3500 mm year^{-1} rainfall, the following equation was developed:

$$\text{AGWB}_2 = 0.0509 \cdot \text{DBH}^2 \cdot H \cdot \rho \quad \text{Eq. (3)}$$

As not all trees of the plot were sampled we estimate the AGWB in relation to the basal area of the sampled trees. This was performed separately for the two diameter classes $\text{DBH} > 30$ cm (>30) and trees with $\text{DBH} 10-30$ cm (<30). Table 3 indicates the number and percentage of all

sampled trees, trees which were sampled for additional wood density determinations and not sampled trees.

For with study we assume that the carbon content ($C_{(\%)}$) of the AGWB depends on wood density (Elias and Potvin 2003) estimated by:

$$C(\%) = (\rho + 16.21)/0.3732 \quad \text{Eq. (4)}$$

To account for possible measurement errors in the field we estimated an error propagation for our AGWB estimates. Errors in measurements of DBH were estimated as 1%, 10% for tree height and the standard deviation of the wood density of the plot for wood density (Schöngart et al. 2011). For allometric models (4) and (5), error propagations for the biomass estimates were calculated as in Schöngart et al. (2011):

$$\sigma^2 \text{AGWB}_{(1)} = (\pi/4)^2 \cdot \left[(\sigma_F \cdot DBH^2 \cdot H \cdot \rho)^2 + (\sigma_{DBH} \cdot F \cdot 2DBH \cdot \rho \cdot H)^2 + \sigma_H \cdot F \cdot DBH^2 \cdot \rho^2 + \sigma_\rho \cdot F \cdot DBH^2 \cdot H^2 \right] \quad \text{Eq. (5)}$$

and

$$\sigma^2 \text{AGWB}_{(2)} = \left[(0.00509 \cdot DBH^2 \cdot H \cdot \rho)^2 + (\sigma_{DBH} \cdot 0.0509 \cdot 2DBH \cdot \rho \cdot H)^2 + \sigma_H \cdot 0.0509 \cdot DBH^2 \cdot \rho^2 + \sigma_\rho \cdot 0.0509 \cdot DBH^2 \cdot H^2 \right] \quad \text{Eq. (6)}$$

2.8 Tree ring analysis and growth modeling

The prepared wood samples for tree-ring analysis were sanded and polished to create a plain surface that enabled the visualization of the annual rings based on the wood anatomical analysis. Wood anatomy of tree rings was characterized following Worbes (2002): (1) Intraannual variations of wood density within a tree ring where wood density increases from earlywood to latewood, typical for the families Annonaceae, Myrtaceae and Lauraceae; (2) tree rings delimited by marginal parenchyma bands commonly observed for species from the families Fabaceae, Meliaceae and Bignoniaceae; (3) alternated bands of parenchyma and fiber tissue, usually with

higher fiber content at the beginning of the tree ring and higher parenchyma contents at the limit of the tree ring commonly observed for the families Sapotaceae, Lecythidaceae, Combretaceae and Moraceae, and (4) ring-porous tree rings with larger vessels in the earlywood and smaller vessels in the latewood, rarely observed in the humid tropics (Fig. 2).

On samples which contained the pith tree age was estimated by direct ring counting. For samples with missing pith we estimated tree age by dividing the obtained average diameter increment rates by the measured DBH in the field. The mean tree age per plot was calculated as the average of the ages of all sampled trees with DBH >30 cm ($Age_{>30}$) and with DBH of 10-30 cm ($Age_{<30}$), weighted by their basal areas ($BA_{>30}$ and $BA_{<30}$) in the plot:

$$Age_{plot} = \frac{(Age_{>30} \cdot BA_{>30}) + (Age_{<30} \cdot BA_{<30})}{BA_{>30} + BA_{<30}} \quad \text{Eq. (7)}$$

Ring widths were measured by a digital measuring device (LINTAB) with 0.01 mm precision attached to a computer with the software Time Series Analysis and Presentation (TSAP-WIN) to determine mean radial increments (Schöngart et al. 2004).

Non-linear regressions were carried out between DBH and tree height using potential equations to produce DBH-height relationships for each plot and module. The relationship between tree age and DBH was fitted to non-linear regression models (Schöngart 2008):

$$Age = a \cdot e^{-b \cdot DBH} \quad \text{Eq. (8)}$$

2.9 Estimation of forest productivity and carbon sequestration

To estimate the AGWB productivity the cumulative diameter growth curve of a tree was combined with the stand-specific DBH-height regression model. Together with the information of wood density it is then possible to estimate for every age along the entire life span the AGWB by the allometric models of Eqs. (2) and (3) (Schöngart et al. 2011). With these models we estimated the age-related aboveground wood biomass production of each tree ($AGWBP_{tree}$) calculating as the average of the difference between the AGWB of consecutive years (t) (Eq. 9).

$$AGWBP_{\text{tree}} = \sum_i^t (AGWB_{i,t} - AGWB_{i,t-1}) / t$$

Eq. (9)

Productivity of the stand was then calculated in two different ways, one to indicate the current total productivity of the stand and one for data analysis to account for the long-term influence of environmental conditions on tree growth and wood biomass increments.

To indicate the current total productivity of the plot ($AGWBP_c$), $AGWBP_{\text{tree}}$ was calculated considering the last five years of the life of each tree (Eq. 9, $t=5$). As not all trees of the plot were sampled we estimate the productivity in relation to the basal area of the sampled trees. This was performed separately for the two diameter classes DBH >30 cm (>30) and trees with DBH 10-30 cm (<30) (Eq. 10). Relating the AGWB productivity per m^2 basal area multiplied by the total basal area in each diameter class gives an estimate of the stand's AGWB production. To account for the long-term influence of environmental conditions on tree growth and wood biomass increment ($AGWBP_m$), $AGWBP_{\text{tree}}$ was calculated considering the whole life span of each tree (Eq. 9). For data analysis, $AGWBP_m$ was calculated by Eq. 11, which divides the whole productivity of the stand by the stand's basal area, as a structural conversion factor (SCF - structural conversion factor; Malhi et al. 2006) to account for high structural differences between the plots (Eq. 11):

$$AGWBP_c = (AGWBP_{>30} \cdot BA_{>30} + AGWBP_{<30} \cdot BA_{<30}),$$

Eq. (10)

$$AGWBP_{\text{mean}} = (AGWBP_{>30} \cdot BA_{>30} + AGWBP_{<30} \cdot BA_{<30}) / (BA_i + BA_j)$$

Eq. (11)

The data analysis was carried out using R-statistics. Graphs were built using Microsoft Excel.

3. Results

Table 4 shows the basal area, mean canopy height, the mean wood density, mean tree age and the non-linear regression models between DBH and tree height for each plot. Tree height was measured for a total of 630 trees. In all four modules DBH explained 56-62% of the variability in tree height with exception of module M08 where the multiple R-squared was only 0.30 (Table 4). Of all sampled trees, one had 214 rings including the pith. Another had 239 rings without reaching the pith, resulting in an estimation of more than 500 years by extrapolating the number of counted rings in relation to the mean radius of the tree trunk. By this calculation, we estimate that from all the sampled trees, 33 would be more than 200 years old. The non-linear relationship between DBH and tree age from all plots was significant ($n=534$, $df=532$, $F=108.65$, $R^2=0.29$, $p<0.01$) (Fig. 3a). Only 30% of the variability of tree age among different species and varying growth condition can be explained by DBH, due to differences in growth rates between species and between individuals of the same species growing in different conditions. This result provides evidence that there is an underlying environmental mechanism determining the formation of tree rings. However, only 30% of variation explained is not enough to consider the model good enough to estimate tree ages in the field only by measuring DBH, independently of the species. Table 5 shows the most common species (with 5 or more occurrences) and their mean wood densities and radial growth. Mean wood density of each plot was significantly related to the mean radial increments of all trees in the plot ($n=8$, $df=7$, $F=11.12$, $R^2=0.75$, $p=0.015$) (Fig. 3b).

Estimates of AGWB resulted in 233 Mg ha^{-1} with a standard deviation of 66 Mg ha^{-1} for the whole study region (Table 6). In relation to the basal area of the stand the AGWB stocks varied $7.6\text{-}12.1 \text{ Mg m}^{-2}_{\text{basal area}}$ (Eq. 3) and $8.2\text{-}13.1 \text{ Mg m}^{-2}_{\text{basal area}}$ (Eq. 4). The estimated AGWBP varies between $3.3\text{-}3.9 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Eq. 2) and $3.5\text{-}4.2 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Eq. 3) in the seasonally flooded forests of module M01. For other plots productivity was much higher varying between $5.5\text{-}6.4 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Eq. 2) and $6.1\text{-}7.1 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Eq. 3). The estimated C-sequestration varied between $1.4\text{-}1.7 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ (Eq. 2) and $1.6\text{-}1.9 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ (Eq. 3) in the two seasonally flooded plots and between $2.4\text{-}2.9 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Eq. 2) and $2.7\text{-}3.2 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (Eq. 3) in the other plots (Table 6). Our estimations of total AGWBP_C resulted in much lower values for the M01

seasonally floodplain plots compared to the plots of other modules. The estimates of AGBW and AGWBP produced by Eqs. (2) and (3) indicate only small differences.

AGWBP was hypothesized to vary with soil structure and hydrology. A strong relation was found between AGWBP_m (calculated from the average of all rings of a tree) and the soil water saturation index (Fig 5a, n=7, df=5, R²=0.83, F=24.24, p<0.01) representing the soil structure (effective depth) and hydrology. The soil water saturation index significantly affects the mean biomass production of the trees, once that increasing values of the index enhance AGWBP_m. (Fig. 4a) and decreases plot's mean age (n=7, df=5, R²=0.78, F=17.78, p<0.01) (Fig. 4b). This pattern was not observed when we related the biomass production of the trees to the HAND data (n=8, df=6, R²=0.04, F=0.25, p>0.05). However, when the two seasonally flooded plots of M01 were removed from the analysis, we observed a relatively strong relation between biomass production of trees and the HAND data following the same pattern as observed with the water saturation index, close to significant (n=6, df=4, R²=0.61, F=6.3, p=0.06). We also notice a relatively strong relation between productivity and the iron concentration on the first 30 cm of the soil, also close to significant. (n=8, df=6, F=5.30, R²=0.47, p=0.06).

4. Discussion

The presented study is the first field-based estimates for tree ages and wood biomass productivity in the vast interfluvial region between the Purus and Madeira rivers. The presented data on tree ages, diameter growth, estimates on AGBW and forest productivity indicate old-growth forests with large stocks of AGBW and relatively high AGWBP, at the range of the nutrient-rich *várzea* floodplains (Nebel et al. 2001; Schöngart et al. 2010) and *paleovárzeas* (Stadtler 2007) (Table 6), despite the low soil fertility of the area (Martins et al. 2012). However, the AGWBP of the studied forests varies considerably between 3.4-6.8 Mg ha⁻¹ year⁻¹ (Table 5).

We found increasing wood biomass productivity with increasing water-logging indicated by the soil water saturation index. This is surprising, since flooding or water-saturated soils cause anoxic conditions (Lambers et al. 2007; Kursar et al. 2008; Haase and Rättsch 2010; Piedade et al. 2010), leading to a decrease in diameter growth (Schöngart et al. 2002) and a decline in forest

productivity, as Stadtler (2007) indicated for the nutrient-poor black-water floodplain forests along a hydrological gradient in the *Amanã* Sustainable Development Reserve, Amazonas state, Brazil. However, the surveillance of tree growth in floodplain forests reveal that trees start growing within the dry season, when forests are still flooded (Schöngart et al. 2002). That could indicate that the conditions of saturation and flooding may generate different responses on tree growth, with water saturation being favorable to tree growth while flooding being unfavorable to tree growth.

The increase in the trees productivity was not observed with the HAND data. However, when not considering the two seasonally flooded plots, the HAND data reveals the same pattern for total ABWBP. Those two referred plots, despite being seasonally flooded, were scored with a lower soil saturation index than another plot that is saturated but not flooded. Therefore, the structure of the soil related to hydrology (i.e. soil depth, drainage and duration of the saturation period) is more important to the productivity of trees than just the level of the water described by the HAND data and height of the water column. Indeed, during field work it became apparent that the HAND data did not describe well the local hydrology related to the smooth topography of the terrain and the flooding of the seasonally flooded plots, and is not a reliable data base to relate hydrology with estimated forest productivity.

Soil water saturation may vary with the soil type and topography of the area. As described by Quesada et al. (2010, 2011), some of the most fertile soils of the Amazon basin may be developed due to bad drainage and deposition of nutrients. Plinthosols, which are quite common in the study region, develop under non-optimal soil conditions by deposition of nutrients like iron molecules (Quesada et al. 2010, 2011). The phosphorus in these soils remains mainly associated with iron molecules and is liberated when the oxidized iron is reduced in the flooded plinthite layer (Chacon et al. 2006). Under this conditions it is thinkable that the hydrological conditions in our study region control the phosphorous availability in the soil, providing more plant-available phosphorous in the most saturated areas. In the generally nutrient-poor soils of the study region (Martins et al. 2012), the release or reduction of one growth-limiting nutrient could possibly be sufficient to have strong impacts on forest growth, and the iron content of the soil could be the main chemical property affecting phosphorous availability for the plants (Chacon et al. 2006). On

well-drained soils, the deposition of iron probably is reduced and as a consequence phosphorus would become more and more unavailable for the roots due to the strong fixation by the present iron molecules, leading to reduced tree growth. A similar pattern was indicated by Clawson et al. (2001) at a semi-deciduous forest in the SW-USA indicating an increase in forest productivity with decreasing soil drainage.

It is also possible that the water-logging of the soils at different depths of the plinthite layer acts as an environmental filter, creating a trade-off where plants would grow faster and present shorter life-cycles. This hypothesis is supported by the strong trend we found between the soil water saturation index and stand age. A high productivity means that trees grow faster and achieve larger diameters at lower ages. Water-logging can lead to shifts in species compositions as it is well known from Amazonian floodplain forests (Wittmann et al. 2006, 2010) towards tree species with higher growth rates and lower life cycles. In this case we would expect a lower wood density of those tree species compared to slow-growing tree species (Gourlet-Fleury et al. 2001) that attain high ages, which is not the case for our studied forests. Still, despite the mean wood density variation among our plots was very low, our results show a strong variation in mean tree growth of the plot with wood density, which suggests that there is probably a shift in species composition. Such variation could be a consequence of water-logging in the soils, leading to species assemblies with faster growth rates and lower life spans due to special adaptations as for instance observed in the central Amazonian *várzea* (Parolin et al. 2004).

A third explanation is that water-logged sites possibly provide a better water supply for tree growth during the dry season as on well-drained sites where tree growth is reduced during the dry season (Brienen and Zuidema 2005). In this case we would expect varying climate-growth relationships between well and poorly drained soils. This is a hypothesis to be tested in future studies applying dendroclimatology for characteristic tree species from different ecotypes between well-drained and water-logged soils in the interfluvial region using traditional tree ring analysis and stable isotopes analyses. We predict that the vegetation period of tree species varies temporarily between different forest types depending on the soil type and hydrological regime such as it was observed between floodplain forests and adjacent *terra firme* forests in Central Amazonia (Schöngart et al. 2004, 2010).

In Table 7 we compare the results for AGWB and AGWBP in this study with other studies in different regions of the Amazon basin. The AGWB stocks in the studied forests of the interfluvial landscape of the Madeira-Purus region are lower than *in terra firme* forests, but higher than in floodplain forests and old fluvial terraces (*paleovárzeas*). Comparing the woody biomass productivity our studied indicate a similar AGWBP as *paleovárzeas* and *várzeas*. In comparison to the flooded and nutrient-poor *igapó* and the central Amazonian *terra firme* forests the studied forest present a higher AGWBP. Only the Southwestern Amazonian *terra firme* forests seem to be more productive, however, as Malhi et al. (2004) applied allometric models which do not consider tree height for the estimates of AGWBP, the values could present biases in the estimates (Schöngart et al. 2010; Feldpausch et al. 2012).

A high natural productivity of a forest system is one of the criteria for the development of sustainable forest management plans (Schöngart and Queiroz 2010). However, the extraction of timber resources in tropical forests as practiced in general is not sustainable (Brienen and Zuidema 2006, 2007; Schöngart 2008; Shearman et al. 2012). In our study region, the most productive sites are encountered where the structure of the soil is worse. The poor structure will probably lead to slow recover of the forest after extracting, and therefore make extraction of timber resources not sustainable. Species and site specific forest managements have to be developed as it was formulated by the GOL-concept (Growth-Oriented Logging) for the high-productive *várzea* floodplain forests of Central Amazonia (Rosa 2008; Schöngart 2008, 2010), that resulted in the Normative Instruction (IN)no. 009. In this forest legislation timber resource management was differentiated for fast-growing tree species with low wood densities (*madeira branca*) and those with high wood densities above 0.60 g cm^{-3} (*madeira pesada*), applying felling-cycles of 12 and 24 years, respectively, and species-specific minimum logging diameters. In our study we show that wood density also is a robust predictor of diameter growth rates. As Table 5 shows, most of the common species of the region present a high wood density ($> 0.65 \text{ g cm}^{-3}$), which would lead to very long felling cycles, based on the GOL concept. Species-specific and site-specific growth models based on tree rings together with studies on the regeneration dynamics and population structure should be performed to evaluate the potential of forest management plans for the region where huge complexes of conservation units have been established allowing the sustainable use of timber resources.

We conclude that AGWBP in the study region is as high as in *várzea* and *paleovárzea* regions that are among the most productive forest types of the Amazon basin. Productivity varies with the hydrological conditions, but it seems that variation in the soil water saturation has even a bigger impact on forest productivity than simply the topographic variation of the terrain. However, it remains unclear to us whether it is hydrological, climatic or edaphic properties or a combination of both that controls productivity of these forests, since the structure of soils of the area is strongly determined by underground water fluctuations.

General global climate models predict a huge impact for the Amazon basin and its carbon stocks and uptakes, mainly due to shifts in the precipitation and hydrological regimes (Dufresne et al. 2002; Betts et al. 2004; Cook et al. 2012). These changes are mainly caused by the increase of sea surface temperature (SST) anomalies in the Equatorial Pacific (Sombroek 2001; Foley et al. 2002; Marengo 2004; Schöngart and Junk 2007) and the tropical Atlantic Oceans (Tomasella et al. 2010; Yoon and Zeng 2010). During the severe drought events in 2005 and 2010, which affected between 2.5 and 3.2 million square kilometers in the Amazon basin, respectively, the interfluvial region between Purus and Madeira Rivers suffered negative precipitation anomalies in 2005 and 2010 (Phillips et al. 2009; Lewis et al. 2011). However, it is unknown how such severe droughts affect the patchwork of floodplain forests, forests on waterlogged soils and well-drained sites. Tree species in Amazonia within the same stand and between ecosystems present varying climate-growth relationships (Worbes 1999; Schöngart et al. 2002, 2004, 2010; Dünisch et al. 2003; Brienen and Zuidema 2005) and may present varying responses to soil saturation (Rodríguez-González et al. 2010). More field data are necessary to relate recruitment and mortality rates to interannual climate and hydrological variation. Such data are essential for the sustainable development of this particular region in terms of timber resource management and conservation as well as future scenarios for carbon stocks, emissions and uptakes due to changes in land-use and climate change.

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Table 1: Geographical position, hydrology and rainfall patterns of the selected study sites at the four studied modules. HAND (Height Above Nearest Drainage) model data indicate the elevation above the nearest drainage (Rennó et al. 2008; Nobre et al. 2011); number in parenthesis indicates the flood height of seasonally inundated forests measured in the field. SRTM (Shuttle Radar Topographic Mission) digital elevation model estimates the altitude above sea level of each plot. The Soil Water Saturation (SWS) index is explained in more detail in Table 2 (no data of the SWS is available for the plot M05.TN500). Rainfall data were obtained from the Brazilian Waters Agency (Agência Nacional de Águas - ANA). Length of the dry season with monthly rainfall below 100 mm was obtained from Magnusson et al. (2009).

Plot ID	Plot Coordinates	SRTM (m)	HAND (m)	SWS Index	Mean annual rainfall (mm)	Length of dry season (months)
M01-TN1500	3°21'3.73"S, 59°50'48.78"W	35.5	1.0 (1.5)	3	2300	3
M01-TN2500	3°20'55.27"S, 59°50'14.58"W	32.2	3.0 (5.0)	3		
M05-TN(-)500	4°36'58.05"S, 43°14'37.44"W	48.9	3.3	-	2810	2
M05-TN1500	4°36'11.82"S, 61°15'28.10"W	50.0	2.0	2		
M08-TS2500	5°38'18.54"S, 62°10'41.24"W	69.4	3.4	1	2600	3
M08-TS4500	5°38'51.38"S, 62° 9'45.25"W	66.6	3.5	2		
M11-TN1500	7°12'24.72"S, 63° 7'0.29"W	72.8	3.8	2	2100	4
M11-TN2500	7°12'38.37"S, 63° 6'30.52"W	69.8	1.6	4		

Table 2. Scores for varying soil physical characteristics and water saturation (adapted from Quesada et al. 2010).

Constantly flooded; patches of stagnated water	4
Seasonally flooded; soils with high clay content and very low porosity and/or dominated by plinthite	3
Deep saturated zone (maximum high saturation of 50 cm deep); redox features	2
Deep saturated zone (maximum high of saturation > 100 cm deep); deep redox features	1
Unsaturated conditions	0

Table 3: Number of sampled and not sampled trees with DBH >30 cm in each plot. Numbers in parenthesis indicate percentages of trees.

Plot code	Number of trees per hectare	Number of sampled trees per hectare	Number of not sampled trees per hectare
M01-1500	65	57 (88)	08 (12)
M01-2500	50	48 (96)	02 (4)
M05-(-)500	57	47 (82)	11 (19)
M05-1500	89	73 (82)	16 (18)
M08-2500	78	53 (68)	25 (32)
M08-4500	89	47 (53)	42 (47)
M11-1500	111	54 (44)	57 (56)
M11-2500	98	48 (48)	50 (52)

Table 4: Basal area per hectare for the diameter classes DBH >30 cm and <30 cm, mean canopy height (H , trees with DBH > 30 cm), mean wood density (ρ) with standard deviation of each plot, mean tree age(Age) and linear regression models between DBH and tree height for each module.

	Plot ID							
	M01-TN1500	M01-TN2500	M05-TN(-)500	M05-TN1500	M08-TS2500	M08-TS4500	M11-TN1500	M11-TN2500
Basal area ($\text{m}^2 \text{ha}^{-1}$)	16	17	22	27	25	28	24	21
Mean Canopy height (m)	25±4.5	24±3.9	27±5.0	28±4.0	28±5.9	25±5.3	32±7.9	27±4.9
ρ (g cm^{-3})	0.65±0.15	0.64±0.13	0.72±0.14	0.71±0.16	0.68±0.13	0.67±0.12	0.65±0.14	0.67±0.16
Age (years)	90	78	106	115	121	105	123	79
Non-linear regression models between DBH and tree height								
	M01	M05		M08		M11		
N	162	145		165		158		
P	< 0.01	< 0.01		< 0.01		< 0.01		
R ²	0.62	0.30		0.62		0.56		
Model	H=4.1244 DBH ^{0.4755}	H=6.8181 DBH ^{0.3681}		H=5.3026 DBH ^{0.4389}		H=3.899 DBH ^{0.5306}		

Table 5: Species with 5 or more individuals sampled in this study and their wood densities (ρ) and mean radial increments (MRI).

Tree species	ρ (g cm ⁻³)	MRI (mm year ⁻¹)
<i>Apeiba echinata</i> Gaertn.	0.44±0.11	3.4±2.4
<i>Bertholletia excelsa</i> Bonpl.	0.61±0.04	1.6±0.6
<i>Brosimum rubescens</i> Taub.	0.56±0.08	1.9±0.4
<i>Buchenavia grandis</i> Ducke	0.71±0.11	2.2±0.8
<i>Diplotropis martiusii</i> Benth.	0.66±0.10	1.7±0.1
<i>Ecclinusa guianensis</i> Eyma	0.69±0.09	1.5±0.9
<i>Erisma bicolor</i> Ducke	0.49±0.07	2.3±1.2
<i>Eschweilera truncata</i> A.C.Sm.	0.77±0.05	1.5±0.5
<i>Eschweilera coriacea</i> (DC.) S.A.Mori	0.81±0.07	1.1±0.4
<i>Goupia glabra</i> Aubl.	0.74±0.06	2.5±1.8
<i>Licania micrantha</i> Miq.	0.84±0.06	1.4±0.1
<i>Licania oblongifolia</i> Standl.	0.90±0.05	1.3±0.5
<i>Pouteria guianensis</i> Aubl.	0.79±0.15	1.3±0.5
<i>Pouteria virescens</i> Baehni	0.80±0.13	1.3±0.4
<i>Pseudolmedia laevis</i> (Ruiz & Pav.) J.F.Macbr.	0.70±0.09	1.1±0.2
<i>Pterocarpus officinalis</i> Jacq.	0.77±0.11	1.5±0.9
<i>Scleronema micranthum</i> (Ducke) Ducke	0.54±0.09	1.4±0.4
<i>Simarouba amara</i> Aubl.	0.40±0.05	3.7±1.9
<i>Sapotaceae</i> sp. 67	0.72±0.09	2.2±1.5

Table 6: Estimates of AGWB and C-stocks in AGWB calculated by Eqs. (2) and (3). For each estimate the error (σ_{AGWB}) is indicated. Furthermore for each plot information on aboveground coarse wood productivity (AGWBP) and carbon sequestration per hectare and year (C-sequestration) and the structural conversion factor ($AGWB_{SCF}$ and $AGWBP_{SCF}$ related to m² basal area) are indicated. Here, $AGWBP_C$ was calculated as the sum of the mean of the productivity of all trees for the last five years, and $AGWBP_{SCF}$ was calculated as the sum of the mean productivity of all trees for the whole life.

	Plot ID							
	M01-TN1500	M01-TN2500	M05-TN(-)500	M05-TN1500	M08-TS2500	M08-TS4500	M11-TN1500	M11-TN2500
Eq. (2)								
AGWB (Mg ha ⁻¹)	134	132	222	281	266	269	289	199
$AGWB_{SCF}$ (Mgm ⁻² _{BA})	8.4	7.6	10.1	10.4	10.8	9.7	12.1	9.7
σ_{AGWB} (Mg ha ⁻¹)	4.0	4.0	4.7	5.0	5.1	3.8	15.2	6.0
C-stock (Mg ha ⁻¹)	61	59	101	128	120	122	130	90
$AGWBP_C$ (Mg ha ⁻¹ year ⁻¹)	4.2	3.5	6.5	6.8	6.1	6.9	6.4	7.1
$AGWBP_m$ (Mgm ⁻² _{BA} year ⁻¹)	0.13	0.11	0.13	0.10	0.10	0.10	0.11	0.14
C-sequestration (Mg ha ⁻¹ year ⁻¹)	1.9	1.6	3.0	3.1	2.7	3.1	2.9	3.2
Eq. (5)								
AGWB (Mg ha ⁻¹)	145	142	240	304	287	290	312	215
$AGWB_{SCF}$ (Mgm ⁻² _{BA})	9.0	8.2	10.9	11.2	11.6	10.4	13.1	10.5
σ_{AGWB} (Mg ha ⁻¹)	4.3	4.4	5.0	5.4	5.6	4.1	16.4	6.5
C-stock (Mg ha ⁻¹)	65	64	109	138	130	131	141	98
$AGWBP_C$ (Mg ha ⁻¹ year ⁻¹)	3.9	3.3	6.0	6.3	5.5	5.8	5.9	6.4
$AGWBP_{mean}$ (Mgm ⁻² _{BA} year ⁻¹)	0.14	0.13	0.14	0.11	0.12	0.12	0.13	0.15
C-sequestration (Mg ha ⁻¹ year ⁻¹)	1.8	1.5	2.7	2.9	2.5	2.6	2.7	2.9

Table 7: Comparison between estimates of AGWB (in Mg ha⁻¹) and AGWBP (in Mg ha⁻¹ year⁻¹) of old-growth forests from this study, with estimates from floodplain forests (*igapó*, *várzea*) and non-flooded sites (*paleovárzeas*, *terra firme*) from other studies. The studies of Stadtler (2007), Oliveira (2010) and Schöngart et al. (2010) applied for the estimates of AGWB and AGWBP Eqs. (2) and (3), while Chambers et al. (2001) and Malhi et al. (2004, 2006) use allometric models with only one (diameter) and two independent variables (diameter, wood density), respectively. SFC (in Mg m⁻²_{BA}) is the structural conversion factor relating AGWB to 1 square meter basal area (BA). The results of other studies that present their values in MgC were doubled to correspond to biomass.

	Area	SFC (Mg m ⁻² _{BA})	AGWB (Mg ha ⁻¹)	AGWBP (Mg ha ⁻¹ year ⁻¹)
This Study	Purus-Madeira interfluvial region	10.8±1.6	252±75	5.6±1.1
Schöngart et al. (2010)	Central Amazonian <i>várzea</i> floodplains	8.8±0.4	235±07	5.7±0.7
Chambers et al. (2001)	Central Amazonian <i>terra firme</i> forests	-	324±36	4.1±0.7
Malhi et al. (2004, 2006)	South Western Amazonian <i>terra firme</i> forests, Peru	10.1±0.6	270±40	7.0±1.5
Stadtler (2007)	Central Amazonian <i>igapó</i> floodplain	8.9±1.6	238±29	3.6±1.2
Oliveira (2010)	<i>Paleovárzeas</i>	7.2±0.2	192± 14	5.4±0.7

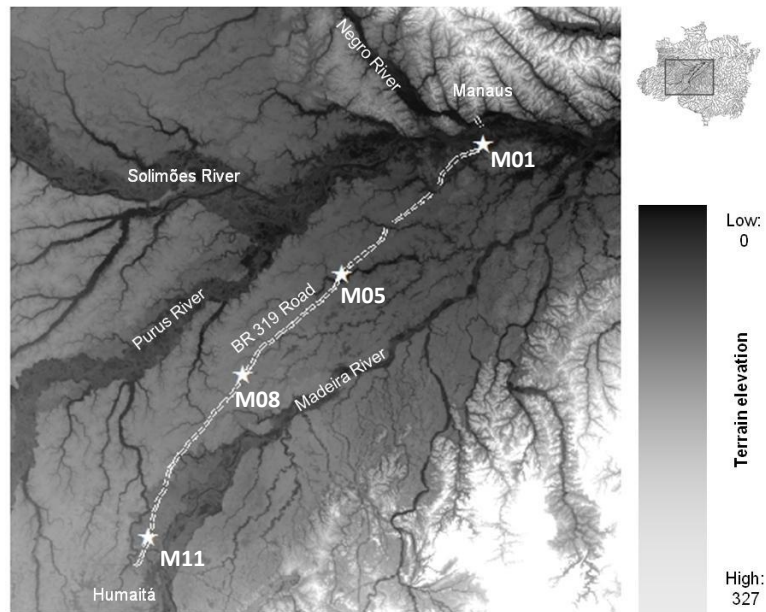


Fig.1. Map of the Purus-Madeira interfluvial area that is crossed by the BR-319 Highway. The study sites are indicated by white asterisks. All study sites are sampling modules (M) of the PRONEX Project Rapid Assessment for Long Duration Ecological Projects (RAPELD).

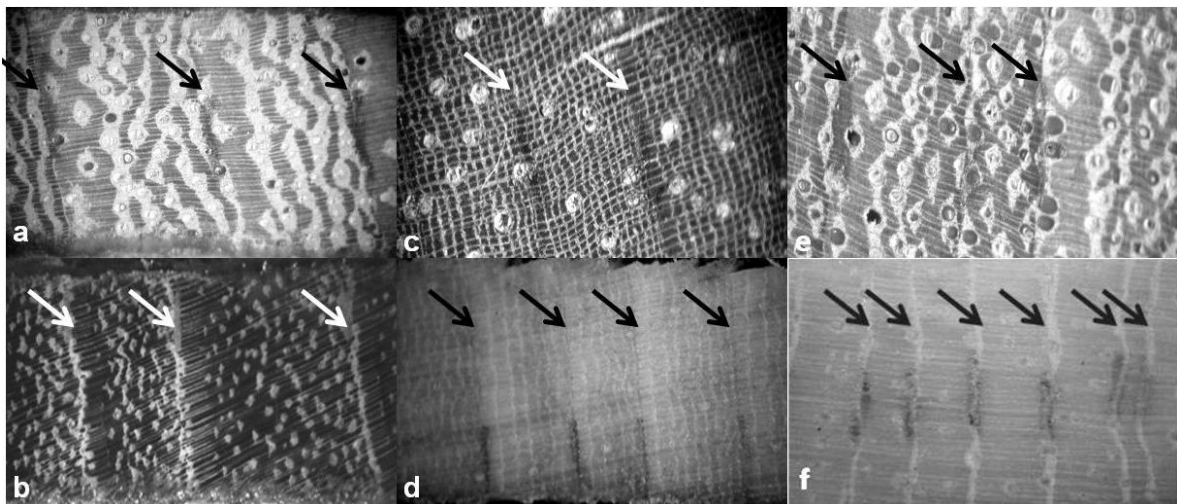


Figure 2: Examples of distinct tree rings. The classification of wood anatomy of the tree rings is described following Worbes (2002): (a, b) Parenchyma bands limiting ring boundaries and vessel size/distribution variation from earlywood to latewood; (c, d) alternating fiber and parenchyma bands, large in the earlywood and narrow in the latewood; (d, e) parenchyma bands defining the ring boundaries.

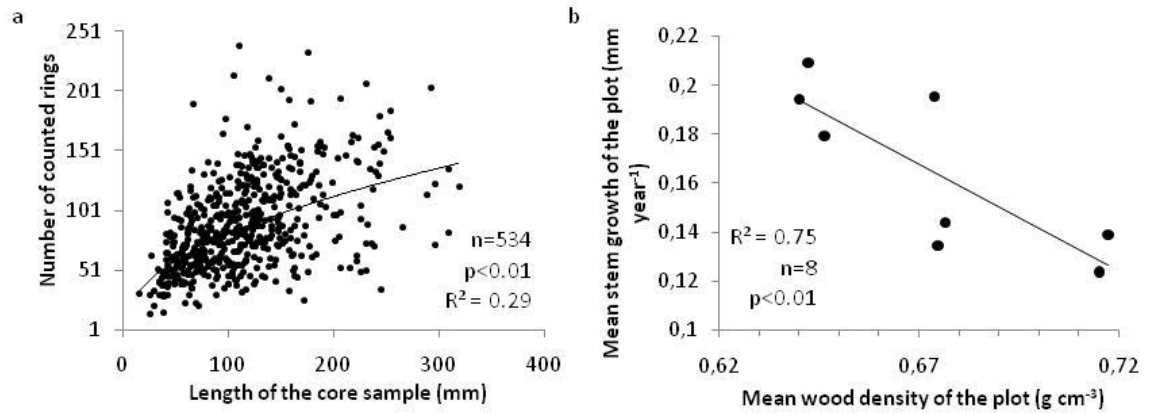


Fig. 3: Significant non-linear relationship between the number of counted rings and length of the core samples for all analyzed trees with distinct growth rings.

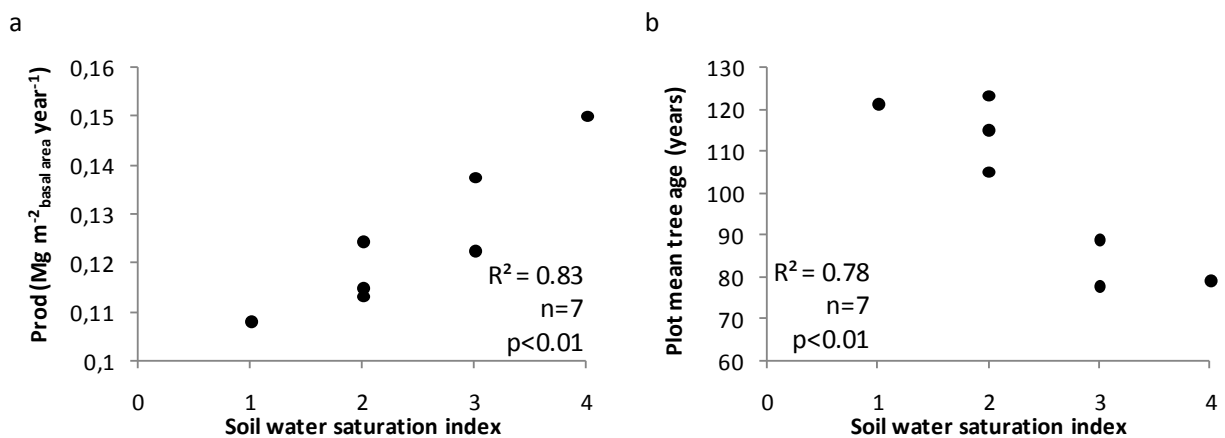


Figure 4: Significant relationship between soil saturations index and (a) mean aboveground wood biomass productivity (AGWBP_m), and (b) plot mean tree age.

Conclusões:

Concluimos que a produtividade acima do solo na área de estudo é tão alta como em florestas de várzea, que estão entre os ambientes mais produtivos da Bacia Amazônica. A produtividade variou com condições hidrológicas do solo, mas parece que estas condições não são bem descritas pela simples variação topográfica do terreno. Sugerimos que a saturação de água no solo tem efeitos diferentes da inundação por vários metros de coluna de água, mas ainda pode levar a formação de diferentes assembléias de árvores com adaptações especiais a solos saturados ou alagados, com espécies que apresentam diferentes taxas de crescimento e duração do ciclo de vida. Entretanto, não está claro se são fatores hidrológicos ou edáficos ou uma combinação de ambos que controla a produtividade na área, já que hidrologia é regulada pela estrutura dos solos da área, mas a estrutura dos solos é fortemente determinada pela flutuação de água do lençol freático durante milhares de anos.

É ainda desconhecido como a floresta do interflúvio irá responder às previsões feitas por modelos climáticos gerais globais, que prevêem um grande impacto para os estoques seqüestros de carbono na Bacia Amazônica, principalmente devido a mudanças no regime de precipitação de hidrológicos. Árvores de um mesmo local podem apresentar uma variedade de respostas ao clima e à saturação do solo, e muitas vezes florestas de ambientes diferentes apresentam relações opostas com o clima, como é o caso de planícies inundadas e florestas de terra firme. Dados sobre recrutamento e mortalidade são necessários para complementar os dados aqui apresentados. Tais dados são essenciais para a implementação das unidades de conservação previstas para a área e para o desenvolvimento de políticas de manejo sustentável das florestas na região.

AULA DE QUALIFICAÇÃO

PARECER

Aluno(a): BRUNO BARÇANTE LADVOCAT CINTRA
Curso: ECOLOGIA
Nível: MESTRADO
Orientador(a): JOCHEN SCHOENGART

Título:

"Produtividade de florestas ao longo de um gradiente hídrico no interflúvio Purus-Madeira".

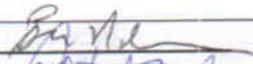
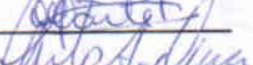
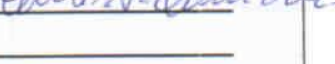
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Manaus(AM), 18 de março de 2011

OBS: _____

Avaliação de dissertação de mestrado

Título: **Produtividade de florestas em gradientes hídricos no interflúvio Purus-Madeira**

Aluno: **BRUNO BARÇANTE LADVOCAT CINTRA**

Orientador: **Jochen Schoengart**

Avaliador: Ana Carolina Maioli Campos Barbosa

Por favor, marque a alternativa que considerar mais apropriada para cada item abaixo, e marque seu parecer final no quadro abaixo


	Muito bom	Bom	Necessita revisão	Reprovado
Relevância do estudo	(X)	()	()	()
Revisão bibliográfica	(X)	()	()	()
Desenho amostral/experimental	(X)	()	()	()
Metodologia	(X)	()	()	()
Resultados	(X)	()	()	()
Discussão e conclusões	(X)	()	()	()
Formatação e estilo texto	()	()	(X)	()
Potencial para publicação em periódico(s) indexado(s)	(X)	()	()	()

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Lavras,
Local

24 de abril de 2012,
Data



Assinatura

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Avaliação de dissertação de mestrado

Título: **Produtividade de florestas em gradientes hídricos no interflúvio Purus-Madeira**

Aluno: **BRUNO BARÇANTE LADVOCAT CINTRA**

Orientador: **Jochen Schoengart**

Avaliador: Carlos Alberto Nobre Quesada (INPA)

Por favor, marque a alternativa que considerar mais apropriada para cada item abaixo, e marque seu parecer final no quadro abaixo

	Muito bom	Bom	Necessita revisão	Reprovado
Relevância do estudo	(x)	()	()	()
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Potencial para publicação em periódico(s) indexado(s)	(x)	()	()	()

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Brasil

ATA DA DEFESA PÚBLICA DA
DISSERTAÇÃO DE MESTRADO DO
PROGRAMA DE PÓS-GRADUAÇÃO EM
ECOLOGIA DO INSTITUTO NACIONAL
DE PESQUISAS DA AMAZÔNIA.

Aos 01 dias do mês de novembro do ano de 2012, às 14:30 horas, na sala de aula do Programa de Pós Graduação em Ecologia - PPG ECO/INPA, reuniu-se a Comissão Examinadora de Defesa Pública, composta pelos seguintes membros: o(a) Prof(a). Dr(a). **Antonio Ocimar Manzi**, do Instituto Nacional de Pesquisas da Amazônia – INPA, o(a) Prof(a). Dr(a). **Philip Martin Fearnside**, do Instituto Nacional de Pesquisas da Amazônia – INPA e o(a) Prof(a). Dr(a). **Laszlo Nagy**, do Instituto Nacional de Pesquisas da Amazônia – INPA/LBA, tendo como suplentes o(a) Prof(a). Dr(a). **Maria Teresa Fernández Piedade**, do Instituto Nacional de Pesquisas da Amazônia – INPA/Max Planck e o(a) Prof(a). Dr(a). Carlos Alberto Nobre Quesada, do Instituto Nacional de Pesquisas da Amazônia – INPA/LBA, sob a presidência do(a) primeiro(a), a fim de proceder a arguição pública do trabalho de **DISSERTAÇÃO DE MESTRADO** de **BRUNO BARÇANTE LADVOCAT CINTRA**, intitulado “Produtividade de florestas em gradiente hídricos no interflúvio Purús-Madeira”, orientado pelo(a) Prof(a). Dr(a). Jochen Schöngart, do Instituto Nacional de Pesquisas da Amazônia – INPA/Max Planck.

Após a exposição, o(a) discente foi arguido(a) oralmente pelos membros da Comissão Examinadora, tendo recebido o conceito final:

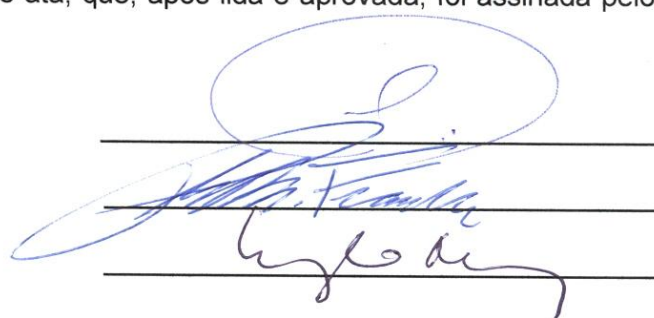
APROVADO(A) REPROVADO(A)
 POR UNANIMIDADE POR MAIORIA


Nada mais havendo, foi lavrada a presente ata, que, após lida e aprovada, foi assinada pelos membros da Comissão Examinadora.

Prof(a).Dr(a). Antonio Ocimar Manzi

Prof(a).Dr(a). Philip Martin Fearnside

Prof(a).Dr(a). Laszlo Nagy





Coordenação PPG-ECO/INPA