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Spatial and temporal dynamics of river channel migration and vegetation in central Amazonian white-water floodplains by remote-sensing techniques

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ABSTRACT

We investigated spatial and temporal migration of the Solimões, the Japurá, and the Aranapu River channels in western Brazilian Amazonia with Landsat TM imagery over a 21-year period. Additionally, we classified and monitored how channel migrations affect the distribution of pioneer vegetation and old-growth forest. The cloud-free study area was 153,032 ha — open water plus 3 km inland on each margin. The channel migration rates, expressed as percent dislocation of the open water body of the river year^{-1}, were lowest in the Japurá River (1.2%), and highest in the Aranapu channel (2.5%), the point bars at river confluence being the most affected landforms subject to geomorphic changes. Annual rates of lateral erosion and accretion of vegetated land along the three rivers were well-balanced. They averaged 0.79 and 0.83% of the cloud-free channel area over the 21 years. The Solimões River was more dynamic than the Japurá River, which can be traced to higher water discharge and sediment load. During the 21 years, the area covered by pioneer vegetation increased by 5.8% of the study area, while late-succession areas decreased by a similar amount (5.5%). According to local biomass estimates of the different vegetation types, these values suggest that C-releases by alluvial erosion would be much higher than C-sequestration caused by the creation of areas suitable for colonization by pioneer vegetation at our study site.

1. Introduction

Amazonian white-water rivers originate from the Andes or the Sub-Andean foothills, and they carry large suspended sediment loads, deposited in lowlands further east. With a water discharge of 70,000–130,000 m^3 s^{-1}, the Ucayali–Solimões–Amazon River is the largest Amazonian white-water river. Above its confluence with the Negro River in central Brazilian Amazonia, it drains an area of approximately 2.2 million km^2 (Latrubesse & Franzinelli, 2002). It is estimated that the annual load of suspended sediment amounts to up to 700 million t (Dunne et al., 1998).

The floodplains influenced by the sediment-rich white-water rivers are called várzea (Sioli, 1954; Prance, 1979). The várzea covers an area of approximately 200,000 km^2, which is 4–5% of the Amazon basin (Junk, 1989; Hess et al., 2003). Due to the comparatively high nutrient content of its substrate and richness in natural resources, the várzea is the ecosystem most densely inhabited by humans within Amazonia (Junk & Piedade, 1997).

The high suspension load of the white-water rivers combined with generally low slopes (2–3 cm km^{-1}, Irion et al., 1997) over most of the Amazon basin result in meandering rivers and consequently a highly dynamic várzea landscape. The rivers are characterized by a mono-modal flood-pulse (Junk et al., 1989), which is the result of precipitation seasonality in the greater part of the catchment area. In central Amazonia, flood amplitudes reach mean heights of up to 10 m, resulting in the periodical inundation of the adjacent lowlands. Therefore, the Amazonian várzea is characterized by a well-defined high-water period (aquatic phase) and a low-water period (terrestrial phase) during the year.

Amazonian white-water rivers undergo rapid spatial and temporal change, as erosion and deposition continually destroy and recreate fluvial forms (Kalliola et al., 1991). Next to the main-river channel of the Ucayali–Solimões–Amazon River, sedimentation on point bars can reach 0.3–1 m year^{-1} (Junk, 1989; Campbell et al., 1992). On undercut slopes, erosion can wash out several hectares of forest during a single high-water period (Wittmann et al., 2004). The unstable habitat conditions caused by the processes of sedimentation and erosion result in a highly diverse patchwork of microhabitats (Campbell et al., 1992), which is reflected by the vegetation cover. In general, sedimentation and substrate texture are linked to both the distance of the sites from the main-river channels and the period of inundation to which the sites are subjected (Mertes et al., 1995; Wittmann et al., 2004). Water current is highest next to the main-river channels, where sedimentation rates are high and relative coarse fractions, such as sand, are deposited at fluvial islands and river banks. With increasing distance from the rivers, current energy is reduced by the

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water resistance posed by levees and the vegetation cover, resulting in decreased sedimentation rates. Simultaneously, fine grains, such as silt and clay, are deposited, especially when the floodwaters are non-turbulent and persist for several weeks or months in oxbows, lakes, and backwater depressions.

Approximately 75% of the várzea is covered by forest. Várzea forests are the most species-rich floodplain forests worldwide (Wittmann et al., 2006). Besides comparatively long floristic evolution since at least the Paleocene (Kubitzki, 1989), it is thought that the exceptional tree species richness in Amazonian várzea can be traced back to the high beta-diversity of the alluvial landscape (Salo et al., 1986; Campbell et al., 1992; Marston et al., 1995) in combination with a moderate disturbance regime imposed on plant assemblages by the annual floods. The distribution of the different várzea forest types is thus determined by adaptations of tree species to different levels and periods of flooding, and most habitats and species are strongly zoned along the flooding gradient (Junk, 1989; Ayres, 1993; Wittmann et al., 2006).

In contrast to undisturbed Amazonian upland forests, where tree regeneration commonly starts in small to medium-sized gaps caused by the mortality of single trees, or collapse of groups of trees in the top canopy, the fluvial dynamism in the várzea continuously creates large areas for new-site colonization. The small-scale changes of sedimentation rates and substrate texture directly influence the distribution of tree species and forest types (Wittmann et al., 2004). On the one hand, drainage in coarse-grained soils is better than in fine-grained soils, where oxygen is rapidly consumed due to the decomposition of accumulated organic matter by microorganisms (Larcher, 1994). On the other hand, sites with coarse-grained substrates normally undergo high sedimentation rates, which impede tree regeneration and cover superficial root layers of mature individuals. Only a few pioneer plants are able to tolerate these environmental conditions, i.e. grasses such as *Echinochloa polystachya* and *Paspalum* spp., and few tree species such as *Alchornea castaneifolia*, *Salix martiana*, and *Cecropia latiloba* in central Amazonian várzea (Wittmann et al., 2004), and *Tessaria integrifolia* in western Amazonian várzea (Lamotte 1990; Kalliola et al., 1991).

The ecologic consequences of river channel migration and alluvial land forms for the biota of the várzea floodplains are still poorly understood (Richards et al., 2002). Studies based on both local measurements and remotely sensed data reported increasing geomorphic activity of the Ucayali–Solimões–Amazon River from central Amazonia toward the western part of Amazonia (Salo et al., 1986; Almeida, 1989; Mertes et al., 1996; Rozo et al., 2005). It is well-known that new-site colonization of freshly deposited sediment by pioneer forest and forest succession within the várzea floodplain strongly depend on the geomorphic dynamism of the white-water rivers (Salo et al., 1986; Kalliola et al., 1991; Campbell et al., 1992). But it is largely unknown to what extent erosion and deposition along the main-river channels affects forest coverage in spatial and temporal scales. However, this knowledge is fundamental for the comprehension of ecosystem processes, e.g., biodiversity modeling and ecosystem fluxes, the monitoring of aboveground woody biomass, and its extrapolation to ecosystem or biome-wide carbon cycle modeling.

In this study, we quantified and monitored alluvial erosion, deposition, river channel migration, and their impact on the distribution of várzea forest types along river bank transects of the Japurá and the Solimões Rivers, western Brazilian Amazonia, by remote-sensing techniques over a 21-year period. The aim of this study was to test whether the geomorphic dynamism of the rivers in this part of the Amazon basin influences the creation and distribution of vegetation types, if variability of erosion and deposition existed over the studied period, and if the ratio erosion/deposition leads to gains or losses of area potentially suitable for vegetation colonization in the studied region. In addition, we use local biomass and carbon-stock estimates of the várzea vegetation to discuss how the geomorphic dynamism of the Japurá and Solimões Rivers influences the carbon-budget of the várzea in this part of the Amazon basin.

2. Methods

2.1. Study area

The study was performed within the Mamirauá Sustainable Development Reserve (MSDR, 02°48′–02°54′ S, 64°53′–65°03′ W), located approximately 550 km W of the city of Manaus, western Brazilian Amazon (Fig. 1). The MSDR is delimited by the Solimões, Japurá and Auati Rivers, the latter being a channel that connects the Solimões to the Japurá River. The MSDR has a size of approximately 1,124,000 ha, and is divided in a subsidiary area (864,000 ha), and a focal area (260,000 ha), separated from each other through a river channel named Aranapu (Fig. 1, Sociedade Civil Mamirauá, 1996).

The entire reserve is located on the Plio-Pleistocene Içá Formation, which is covered by unconsolidated alluvial sediment of the Solimões and the Japurá rivers (Rossetti et al., 2005). Mean monthly temperatures in the MSDR vary a little over the year and range between 25 and 28 °C, mean annual rainfall amounts to approximately 3000 mm (Wittmann & Junk, 2003).

Annual water-level fluctuations of the Solimões and Japurá Rivers averaged approximately 11 m since 1993 (Institute for Sustainable Development Research at Mamirauá — ISDRM). Variations in geomorphology, pedology, and the vegetation cover of the MSDR are directly related to the mechanisms of deposition and fixation of the alluvial substrate. Next to the river banks, eutrophic substrates are mainly composed of fine sand, whereas silt- and clay-rich hydromorphic gleys dominate further inland. The substrate clay fraction in the MSDR ranges from approximately 30% at the river banks up to 83% further inland (Wittmann et al., 2004). Due to the high variability of the hydraulic relations within the extensive floodplain, the landscape of the MSDR is a patchwork of recent fluvial linear channel-bars that are intercalated with levees, ancient channel-bars, oxbows, and lakes, periodically interconnected with each other and the main-river system (RADAMBRASIL, 1977). About 90% of the focal area of the MSDR is covered by different forest types (Sociedade Civil Mamirauá, 1996). The vegetation cover near the lower banks of the river channels is dominated by aquatic and semi-aquatic macrophytes (herbaceous grasses, with dominance of *E. polystachya* and *Paspalum* spp.), and the pioneer tree species *A. castaneifolia, S. martiana* and *C. latiloba*, which mostly form mono-specific stands (Wittmann et al., 2002, 2004). These pioneer tree species establish at mean maximum flood-levels of approximately 5–7 m water depth, and their stems and aboveground roots secure the deposited alluvial sediment (Wittmann et al., 2004). Floristic inventories in combination with tree-age determinations derived through dendrochronological methods indicate that mean maximum stand ages of pioneer forest types is about 10–15 years when dominated by *A. castaneifolia* and *S. martiana*, whereas it is about 25 years when dominated by *C. latiloba* (Worbes et al., 1992; Schöngart 2003). These pioneer forest types were estimated to cover 29% of the focal area of the MSDR (Wittmann et al., 2002).

2.2. Image processing and mask choice

The study was performed utilizing Landsat 5 Thematic Mapper (TM) image data for the scene at path 1, row 62, provided by the National Institute for Space Research — INPE. Four of the sensor's bands were employed: 3 (red), 4 (near-infrared), 5 (mid-infrared) and 7 (mid-infrared). We acquired six images of this scene, all dating to periods at or near low-water stage (September–November), between 1984 and 2005 (Table 1). At our study site, water levels of the rivers recede beginning in mid June to early July. Water-level minima generally occur between October and November (IBGE, 1991). Only images with cloud cover <20% were used.