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1 **Contribution of meandering rivers to natural carbon fluxes: evidence from the Ucayali**  
2 **River, Peruvian Amazonia**

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17 **Contribution of meandering rivers to natural carbon fluxes: evidence from the Ucayali**  
18 **River, Peruvian Amazonia**

19 **1. Abstract**

20 Better understanding the fate of the atmospheric carbon (C) captured by plant photosynthesis  
21 is essential to improve natural C flux modelling. Soils are considered as the major terrestrial  
22 bioreactor and repository of plant C, whereas channel networks of floodplain rivers collect and  
23 transport, throughout the aquatic continuum, a significant part of plant primary production until  
24 its export through outgassing or sequestration in marine sediments. Here, we show that river  
25 meandering in forested floodplains is a crucial and widely overlooked Earth surface process  
26 promoting C fluxes from the atmosphere to the aquatic continuum, via the floodplain  
27 vegetation. Over a recent period of 35 years (1984-2019), we quantified those C fluxes in one  
28 of the most active meandering rivers on Earth, the Ucayali River, Peru, South America. We  
29 used map time series combined with above-ground forest C data to derive the amount of C that  
30 is annually captured by the growing floodplain vegetation within the active meander belt, as  
31 well as exported to the aquatic continuum by lateral channel erosion. We found that the annual  
32 building and erosion of forested floodplain areas was nearly balanced over time with  
33  $19.0 \pm 7.7 \times 10^3 \text{ ha}^{-1} \text{ yr}^{-1}$  and  $19.8 \pm 6.7 \times 10^3 \text{ ha}^{-1} \text{ yr}^{-1}$ , respectively. While growing forests within  
34 the active meander belt annually captured  $0.01 \pm 0.05 \times 10^6 \text{ Mg C yr}^{-1}$ , lateral channel erosion  
35 provided the nearly 100-fold amount of C to the river channel and its streamflow, i.e.  
36  $0.9 \pm 0.4 \times 10^6 \text{ Mg C yr}^{-1}$ . Our findings revealed that the migration of the Ucayali River channel  
37 provided nearly 10-times more lignified C per unit area to the aquatic continuum ( $44.7 \pm 21.4$   
38  $\text{Mg C ha}^{-1} \text{ yr}^{-1}$ ) than non-meandering central Amazonian floodplains do. Together, these  
39 findings point to the importance of quantifying the overall contribution of meandering rivers to  
40 natural C fluxes worldwide.

## 41    **2. Introduction**

42    Floodplains are areas of high primary production which provide fresh autochthonous carbon  
43    (C) to river waters through litterfall, plant and micro-organism respiration (Abril *et al.*, 2014).  
44    Levels of plant production in floodplains and the extent of the floodplain area can therefore  
45    considerably modulate the overall C quantity found in river waters (Ward *et al.*, 2017). Hence,  
46    floodplain vegetation, algae and floating macrophytes in highly productive and preserved  
47    tropical areas, directly and rapidly provide organic and inorganic C to rivers (Abril *et al.*, 2014;  
48    Sawakuchi *et al.*, 2017). Abril *et al.* (2014) further suggested that central Amazonian wetlands  
49    export half of their gross primary production to rivers, being the primary sources for CO<sub>2</sub>  
50    outgassing by the Amazon.

51    Over the last decade, several studies successively updated regional and global estimates of river  
52    C fluxes from land to oceans (Drake *et al.*, 2018). These studies underscored large data gaps  
53    and uncertainties, suggesting that C fluxes might be much larger than previously thought. In  
54    particular, uncertainties in the contribution of wetlands and macrophytes as a source of C for  
55    rivers has been highlighted (Spencer *et al.*, 2013) and the need for new investigations identified.  
56    Furthermore, river meandering, among other processes contributing to C input into rivers, river  
57    meandering remains however a largely overlooked Earth surface process (Peixoto *et al.*, 2009).  
58    Yet, this process is recognized in sculpting the Earth surface since more than 5 centuries, and  
59    studies have recently pointed out its potential role in biogeochemical fluxes (Iepi & Lapôte,  
60    2019). Abiotic factors, like sedimentary dynamics in meandering rivers, have been suggested  
61    as essential than biotic factors, like productivity and respiration, in the terrestrial organic C  
62    cycle (Torres *et al.*, 2017; Iepi & Lapôte, 2019).

63    Typically, meandering rivers are characterized by lateral bank erosion occurring at the outer  
64    meander bends, whereas lateral accretion processes form point bars within inner meander bends  
65    (Leopold and Wolman, 1960; Allen, 1965). Within the Amazon basin, lateral channel migration

66 generates meander scrolls forming a sequence of ridges and swales, on which a sequential  
67 primary forest succession of high productivity rapidly takes place (Salo *et al.*, 1986; Junk *et al.*,  
68 1989; Puhakka *et al.*, 1992). Forest succession, leading eventually to the mature stage, continues  
69 when the channel further migrates and point bars are integrated into the floodplain. Conversely,  
70 channel migration also causes bank erosion which in turn promotes direct massive inputs of  
71 coarse woody material to river channels, thus providing substantial quantities of autochthonous  
72 C, potentially exceeding those imported through litterfall and respiration. Active river  
73 meandering closely linked to point bar formation, floodplain aging and lateral channel erosion,  
74 thus presents a relevant Earth surface process to consider for accurately quantifying and  
75 understanding floodplain C sequestration and its export to the aquatic continuum (Wohl *et al.*,  
76 2013; Sutfin *et al.*, 2016).

77 Here, we aimed to provide evidence that river meandering in Amazonian floodplains  
78 significantly contributes to river C budgets. Our objective was to quantify the amount of C that  
79 annually accumulates in the forest biomass, as well as the part that is annually exported to the  
80 river channel, within the active meander belt of the river, i.e. the area where contemporary  
81 channel migration occurred. We investigated one of the major active tributaries of the Amazon,  
82 the Ucayali River, Peru, over a period of 35 years (1984-2019). We used the yearly water  
83 classification history dataset provided by the Joint Research Centre to produce annual maps of  
84 point bar formation, floodplain ages and river channel erosion in the 1984-2019 active meander  
85 belt. Annual maps were combined with a model predicting the living above-ground forest C  
86 stock from the floodplain age to derive amounts of C annually fixed by net primary production  
87 and exported to river waters after bank erosion. The quantity, quality and fate of the C provided  
88 by Amazonian meandering rivers to the aquatic continuum is discussed in respect to the existing  
89 literature.

### 90 **3. Method**

### 91 3.1. Study area

92 The Ucayali River is located in the western part of the Amazon basin (Fig. 1a). It is a major  
93 tributary of the Amazon River extending approximately 900 km from its upstream confluence  
94 with the Rio Tambo and Rio Urubamba to its downstream confluence with the Marañón River.  
95 The mean annual water discharge is about  $12\,100\text{ m}^3\text{ s}^{-1}$  and water depth between low and high  
96 flood flows can range from 8 to 15 m (Santini *et al.*, 2019). The maximum and minimum  
97 monthly flows, recorded over the 1996-2018 period at the Requena gauging station, is of 22 900  
98 and  $2\,500\text{ m}^3\text{ s}^{-1}$  respectively (HYBAM, 2020). Close to the town of Pucallpa, the floodplain  
99 width is about 25 km and the active meander belt is approximately 10 km in width (Fig. 1b, c).  
100 The Ucayali is considered as one of the last pristine free meandering white-water rivers  
101 worldwide, characterized by high suspended sediment loads, nutrient-rich waters and high  
102 lateral channel migration rates within an unconstrained, forested floodplain (Constantine *et al.*,  
103 2014). Within meandering floodplain rivers, forest primary succession is distinctly age-zonated  
104 (Salo *et al.*, 1986; Junk *et al.*, 1989; Puhakka *et al.*, 1992). The vegetation succession progresses  
105 from early successional stages dominated by short-lived species to latter successional stages  
106 dominated by long-lived species along a cross-river and age gradient (Salo *et al.*, 1986;  
107 Lamotte, 1990; Fig. 2). The early stage of primary succession begins on newly formed alluvial  
108 bars, mainly point bars, rapidly colonized by *Tessaria integrifolia* L. and *Gynerium sagittatum*,  
109 forming dense canopies of about 5-8 m in height. This early pioneer stage is replaced by a  
110 second stage dominated by *Cecropia tessmannii*, forming a closed canopy of about 14-18 m in  
111 height. The *Cecropia* forest is located on older meander scrolls in backwater depressions.  
112 During these two first stages, vegetation contributes to sediment and organic matter trapping,  
113 which leads to floodplain construction and soil C sequestration (Fig. 2; Salo *et al.*, 1986). The  
114 following stage is a mixed forest dominated by *Ficus insipida* and *Cedrela odorata*, forming a  
115 closed canopy of about 20-25 m in height. At this stage, floodplain surface elevation is about 5

116 m above the low water level. Its topography is more homogeneous compared to the pioneer  
117 zone in the previous stages of succession. This is due to the deposition of large amounts of silt  
118 in backwater depressions during seasonal flooding. The later successional mixed forest is more  
119 diversified and composed of large trees with a canopy of about 40 m in height. Soil topography  
120 of the floodplain at this level (> 5-10 m above the low water level) is generally flat with only  
121 minor remaining depressions. This forest succession trajectory is basically the same at each  
122 meander of the Ucayali River (Kalliola *et al.*, 1991). Lateral channel erosion leads to a  
123 continuous reset and regeneration of the primary vegetation succession over large areas (Salo  
124 *et al.*, 1986; Kalliola *et al.*, 1991). Since point bars of the Ucayali River are either rapidly eroded  
125 or integrated into the forested floodplain during lateral channel migration, we will, hereafter,  
126 exclusively distinguish the river channel from its floodplain, including point bars.

### 127 3.2. Mapping floodplain formation, aging and erosion

128 We used the yearly water classification history dataset (v1.2) provided by the Joint Research  
129 Centre (JRC) and freely available on the Google Earth Engine (GEE) platform (Gorelick *et al.*,  
130 2017). This dataset was firstly created by Pekel *et al.* (2016) and now consists in 36 annual  
131 raster maps spanning the 1984-2019 period. Pixels size approximately 900 m<sup>2</sup> at ground level  
132 and are classified in ‘no data’, ‘non-water’, ‘seasonal water’ or ‘permanent water’ (Fig. S1 in  
133 Appendix A). In order to create an envelope for data extraction, we firstly downloaded  
134 geometries (i.e. polylines shapefiles) of the Ucayali River from the Open Street Map database  
135 available at <https://download.geofabrik.de>. Then, we created a 10-km buffer across the river  
136 using the ArcGIS software package (ESRI, Redland, USA). The yearly water classification  
137 history dataset overlaying the river buffer was finally downloaded from the GEE platform.  
138 Using the MatLab software package (Mathworks, Natick, USA), the 36 annual raster maps were  
139 proceeded in order to map annual areas of floodplain formation, ages and erosion. The

140 algorithm was applied pixel-by-pixel and year-by-year as illustrated in Figure 3. Pixels that  
141 were classified as ‘seasonal water’ or ‘permanent water’ at a given year (e.g. 1984; Fig. 3a),  
142 and classified ‘non-water’ the following year (e.g. 1985), were mapped as 1-year-old pixels.  
143 Each year from 1985 to 2019, every pixel age-determined at a given year (e.g. 1-year-old in  
144 1985) and remaining ‘non-water’ the following year (e.g. 1986) was incremented with one  
145 additional year (e.g. 2-year-old in 1986). Remaining ‘non-water’ and ‘no data’ pixels with no  
146 age between successive years (e.g. between 1984 and 1985) were set to age ‘non-determined’  
147 (ND). Typically, ND pixels corresponded to floodplain and upland areas created before 1984.  
148 Each year, from 1985 to 2019, every pixel age-determined at a given year (e.g. 2-year-old in  
149 1986) and classified ‘seasonal water’ or ‘permanent water’ the following year (e.g. 1987) was  
150 considered as an eroded area (Fig. 3b) and reset to age 0 (e.g. 0-year-old in 1987).

### 151 3.3. Deriving C-stocks from floodplain ages

152 In line with Pahukka *et al.* (1992), we assumed that on the Ucayali River, pioneer vegetation  
153 colonizes bare alluvial bars from the year of their creation (Fig. S2 in Appendix A). We thus  
154 considered that the vegetation age is equal to the floodplain age. We used published data to  
155 predict the forest above-ground carbon stock (C-stock in Mg C ha<sup>-1</sup>) from the floodplain age  
156 (age in years), and constructed a model predicting C-stock as a function of age (Fig. 3c). The  
157 data were published by Schöngart and Wittmann (2010) and based upon thousands of in situ  
158 vegetation structure inventories and tree ring measurements within floodplains of central  
159 Amazonia. Forest above-ground carbon stocks were estimated in several, almost undisturbed  
160 successional stages, with stands varying between 7 and 240 years of age. Forest structure data  
161 and several allometric models were used to construct a data series of C-stocks per forest age.  
162 First, we extracted data from the figure 18.10 presented by Schöngart and Wittmann (2010)  
163 using Web Plot Digitizer 4.3 software (Ankit Rohatgi, Pacifica, California, USA). Second, we



164 fitted a 3<sup>rd</sup> order polynomial model to the 35 first years of the data series. These 35 years  
165 corresponded to the forest establishment that we analysed on the Ucayali River between 1984  
166 and 2019. For floodplain forests established before 1984 (ND ages; Fig. 3a, b), we assumed a  
167 constant C-stock, i.e. old-growth forests with ages > 70-year-old in the data series. This  
168 assumption was based on the floodplain age structure of eroded outer meander bends presented  
169 in the results section.

### 170 3.4. Annual accumulation of floodplain forest C-stocks and its erosion

171 Floodplain areas were converted into above-ground forest C-stocks based on our model (Fig.  
172 3c). The annual total C-stock (in Mg C ha<sup>-1</sup>) was obtained by summing C-stocks of all vegetated  
173 floodplain ages since 1984. An annual C accumulation rate was obtained by (1) subtracting the  
174 total C-stock of year n by the one of year n-1, and (2) by applying a linear regression and the  
175 calculation of the root mean square error (RMSE). C-accumulation in floodplain and upland  
176 forest areas established before 1984 were not considered in the present study because they were  
177 outside of the 1984-2019 active-meander belt. Annual C-stock lost through floodplain erosion  
178 was obtained by summing eroded C-stocks of determined and non-determined (ND) floodplain  
179 ages.

## 180 4. Results

### 181 4.1. Annual vegetated floodplain area formation and erosion

182 Over the 1984-2019 period, the water surface area of the Ucayali River accounted for  $220 \pm 25$   
183  $\times 10^3$  ha (annual average and its standard deviation; Appendix B). Maximum water surface area  
184 extensions were observed in 1988, 1994, 2001, 2011, 2017 and minimums in 1987, 1992, 1997,  
185 2005, 2010, 2013 and 2018 (Fig. 4a). Negative anomalies appeared mainly before 2000 and  
186 positives anomalies mainly after 2000. Yearly formation of floodplain areas occurred mainly

187 within inner meander bends and accounted in average for  $19.0 \pm 7.7 \times 10^3 \text{ ha}^{-1} \text{ yr}^{-1}$  (Fig. 4b; Fig.  
188 5; Appendix B and C). Conversely, floodplain erosion was located mainly in outer meander  
189 bends and closely balanced floodplain formation with an average of  $19.8 \pm 6.7 \times 10^3 \text{ ha}^{-1} \text{ yr}^{-1}$   
190 (Fig. 4c; Appendix B and C).

#### 191 4.2. Age structure of vegetated floodplain areas

192 We found that meandering promotes rejuvenation and recurrent formation of large areas of bare  
193 alluvial bars that are quickly colonized by pioneer vegetation. Over the 1984-2019 period, ages  
194 of floodplain areas were unevenly distributed (Fig. 6a). One-year-old floodplain areas largely  
195 dominated. However, about 1/3 of these newly formed floodplain areas were eroded the  
196 following year. Indeed, we found that older age classes generally decreased in areas following  
197 a negative logarithmic trend (Fig. 6a). This trend resulted from floodplain erosion (Fig. 6b).  
198 Newly established floodplain areas at inner meander bends were primarily affected by erosion  
199 at a rate of  $6.4 \pm 3.3 \times 10^3 \text{ ha}^{-1} \text{ yr}^{-1}$ , i.e. 1/3 of the yearly formed floodplain surface area  
200 ( $19.0 \pm 7.7 \times 10^3 \text{ ha}^{-1} \text{ yr}^{-1}$ ). The rate of erosion decreased from younger to older floodplain areas  
201 (Fig. 6b). Floodplain erosion occurred equally in outer meander bends and in areas established  
202 before 1984, i.e. non-determined in age (ND) in the present study. Erosion in areas of ND ages  
203 accounted annually for about  $7.0 \pm 3.8 \times 10^3 \text{ ha}^{-1} \text{ yr}^{-1}$  (Fig. 6b; ND).

#### 204 4.3. Annual changes in floodplain forest C-stocks

205 Our model used to derive C-stocks from floodplain ages showed a very good adjustment to the  
206 data ( $R^2 = 0.99$ ; Fig. 7). One-year-old vegetation accounted for an average of  $0.7 \text{ Mg C ha}^{-1}$  and  
207 increased to  $95.3 \text{ Mg C ha}^{-1}$  at 35-year-old. Old-growth floodplain forests, i.e. those that  
208 established on areas older than 70-year-old, levelled off at nearly  $115 \text{ Mg C ha}^{-1}$  (Fig. 7). We  
209 combined annual maps of floodplain ages with our C-stock model and produced annual maps  
210 of above-ground C-stocks (Fig. 8). The mean annual C accumulation rate of floodplain forests

211 established after 1984 in the Ucayali 1984-2019 active meander belt was estimated at  $0.01 \times 10^6$   
212  $\text{Mg C yr}^{-1}$  with a RMSE of  $0.04 \times 10^6 \text{ Mg C yr}^{-1}$  (Fig. 9a). Given the relation between available  
213 floodplain area and C-stock, the generation with the most effective C-sequestration capacity  
214 was the 23-year-old forest (Fig. 9b). Annual floodplain erosion caused by lateral channel  
215 migration accounted approximately for  $0.9 \pm 0.4 \times 10^6 \text{ Mg C yr}^{-1}$  (Fig. 10a). Floodplain areas  
216 which established before 1984 largely dominated eroded C-stocks with  $0.8 \pm 0.4 \times 10^6 \text{ Mg C yr}^{-1}$   
217  $^1$  (ND; Fig. 10b).

## 218 **5. Discussion**

### 219 5.1. Annual floodplain formation balances annual floodplain erosion in area but not in C 220 budget

221 We found that rates of annual floodplain formation and rates of annual floodplain erosion  
222 appeared to be in balance over time with  $19.0 \pm 7.7 \times 10^3 \text{ ha}^{-1} \text{ yr}^{-1}$  and  $19.8 \pm 6.7 \times 10^3 \text{ ha}^{-1} \text{ yr}^{-1}$ ,  
223 respectively. Our results confirm those reported by Puhakka *et al.* (1992) who showed that outer  
224 banks and point bars have, respectively, roughly equivalent rates of erosion and sediment  
225 deposition, maintaining a relatively constant channel width. Similarly, Peixoto *et al.* (2009) and  
226 Schwenk *et al.* (2017) reported an annual balance of erosion and deposition over large study  
227 areas and multidecadal periods. Peixoto *et al.* (2009) suggested that annual release of C caused  
228 by river dynamics would be much higher than the C annually sequestered within the floodplain.  
229 Our results have quantitatively confirmed their hypothesis. Indeed, within the 1984-2019 active  
230 meander belt of the Ucayali River, the floodplain forest annually accumulates  $0.01 \pm 0.04 \times 10^6$   
231  $\text{Mg C yr}^{-1}$  and exports  $0.9 \pm 0.4 \times 10^6 \text{ Mg C yr}^{-1}$ . Although it appeared that there is a balance in  
232 areas between floodplain formation and erosion, we show that there is however a strong  
233 imbalance in rates of floodplain forest C fixation and export to river waters caused by lateral

234 channel migration. This imbalance is mainly due to massive erosion of old-growth floodplain  
235 forests with high C-stock densities (about 115 Mg C ha<sup>-1</sup>).

## 236 5.2. Lateral channel migration as a significant C provider to the aquatic continuum

237 There are multiple C sources for the aquatic continuum, i.e. between aquatic ecosystems from  
238 the atmosphere, headwater streams and inland waters, to coastal and marine systems. First, the  
239 C conveyed to streams and rivers can be provided during precipitation where water drops can  
240 be enriched in dissolved and particulate organic C (DOC, POC; Ward *et al.*, 2017). Then, when  
241 entering forest canopies, drops capture DOC and POC at the surface of leaves, branches and  
242 trunks. By instance, in the Rio Negro region, throughfall fluxes of 27.5 kg C ha<sup>-1</sup> yr<sup>-1</sup> have been  
243 reported (Filoso *et al.*, 1999). Throughfall fluxes that range between 68.4 and 195.1 kg C ha<sup>-1</sup>  
244 yr<sup>-1</sup> and stem flow fluxes of 1.5 kg ha<sup>-1</sup> yr<sup>-1</sup> have been also reported in Amazonia (Neu *et al.*,  
245 2016). In addition to the C provided by rainfall, root and canopy litterfall and respiration in  
246 floodplain forests together with algal and floating macrophyte communities are considered as  
247 the main C pathways to the aquatic continuum (Ward *et al.*, 2017).

248 Even though they represent only about 14 % of the Amazon basin, floodplains are highly  
249 productive compared to terrestrial uplands and are hydrologically connected to river channels  
250 during yearly overbank flooding (Richey *et al.*, 1980; Junk, 1985; Hoffmann *et al.*, 2009). It  
251 has been reported that in Central Amazonia, floodplains can provide an amount of 59.6±38.7  
252 Mg C ha<sup>-1</sup> yr<sup>-1</sup> to the channel network and streamflow (Abril *et al.*, 2014). Here, we point out  
253 that lateral channel erosion is a crucial and overlooked physical driver delivering large amounts  
254 of C to rivers. We show that channel migration in the upper Amazonian floodplain provides  
255 between 0.7 and 115 Mg C ha<sup>-1</sup> yr<sup>-1</sup> to streamflow depending on the age of the forested  
256 floodplain areas eroded. Over the studied period and area, we found that in average 44.7±21.4  
257 Mg C ha<sup>-1</sup> yr<sup>-1</sup> was delivered by lateral channel erosion to the aquatic continuum (0.9±0.4×10<sup>6</sup>

258 Mg C yr<sup>-1</sup> delivered over  $19.8 \pm 6.7 \times 10^3$  ha<sup>-1</sup> yr<sup>-1</sup>). Our result is roughly equivalent to the amount  
259 provided by the entire wetland system of the central Amazonian floodplain (i.e. flooded forest  
260 and macrophytes litterfall and respiration;  $59.6 \pm 38.7$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>), and roughly 10 times  
261 higher than the amount of the woody part considered by Abril *et al.* (2014) i.e.  $5.3 \pm 2$  Mg C  
262 ha<sup>-1</sup> yr<sup>-1</sup>.

263 The amount of C provided by meandering rivers is dependant on annual rates of floodplain  
264 erosion. In the Amazon basin, different rates of channel migration of white-water rivers have  
265 been observed to exponentially increase from east to west (Kalliola *et al.*, 1992; Mertes *et al.*,  
266 1995; Peixoto *et al.*, 2009; Salo and Räsänen, 1989). Therefore, inputs of woody materials as a  
267 consequence of lateral channel erosion may certainly increase along a downstream-upstream  
268 gradient. Further studies are thus required to quantify the spatial variability and overall  
269 contribution of Amazonian meandering rivers. Here, we have calculated the contribution of  
270 above-ground forest biomass to streamflow, but further amounts of C input may originate from  
271 (i) eroded floodplain soils (i.e. belowground total organic matter; Fig. 2), and (ii) the Andean  
272 mountains situated upstream the study area, where torrential streams potentially accumulate  
273 and transport large amounts of coarse woody debris provided by landslides occurring in  
274 particular during tropical storm events (McClain and Naiman, 2008; Clark *et al.*, 2013; Wohl  
275 and Ogden, 2013).

### 276 5.3. Nature and fate of the C provided by meandering rivers

277 The nature of the C that is annually exported into the aquatic continuum is a fundamental aspect  
278 when considering the fate of this C and its role in the global cycle. It is usually considered that  
279 river C is advected downstream and returned to the atmosphere *via* degassing by both microbial  
280 and photochemical activity, ultimately resulting in a net zero exchange, especially in the tropics  
281 where warm temperatures stimulate organic matter decomposition (Raymond *et al.*, 2013; Ward

282 *et al.*, 2013). For instance, Abril *et al.* (2014) proposed that central Amazonian waters receive  
283 at least as much C from wetlands as they emit to the atmosphere, making a nearly neutral  
284 balance in atmosphere-biosphere CO<sub>2</sub> exchanges. However, the C provided by meandering  
285 rivers of the upper Amazon basin most probably differs from the C provided by wetlands of the  
286 central Amazon. On the one hand, it has been shown for wetlands of the central Amazon that  
287 the microbial communities decompose young organic C (> 5-year-old; Mayorga *et al.*, 2005;  
288 Abril *et al.*, 2014). On the other hand, the organic C found in the water column mainly originates  
289 from litterfall with low lignin content (Mayorga *et al.*, 2005; Abril *et al.*, 2014). Our results  
290 suggest that in free meandering Amazonian rivers, such as the Ucayali River, older lignin is  
291 present in substantial quantities. Higher concentrations of lignin are found in tree trunks,  
292 branches and roots of ligneous terrestrial plants, and we estimated that mature and old growth  
293 floodplain forests accounted for nearly half of the eroded floodplain area within the Ucayali  
294 1984-2019 meander belt (Fig. 6b). However, the fate of these large C quantities of lignin  
295 remains still uncertain. One hypothesis could be that this C is mineralized by microbial and  
296 photochemical activity and/or exported downstream the aquatic continuum and/or accumulated  
297 in the river sediment. Following Ward *et al.* (2013), half of these quantities could be degraded  
298 and mineralized in the Amazon River. Anyhow, according to Galy *et al.* (2015), the erosion  
299 and transportation capacities of rivers are to be considered as the main control of the biospheric  
300 C export to oceans. Many large water storage reservoirs have been recently proposed for the  
301 Amazon Basin (Finer and Jenkins, 2012). Since meandering rivers are known to be highly  
302 sensitive to the disruption of sediment supply caused by such engineering projects (Constantine  
303 *et al.*, 2014), it is highly suspected that such human infrastructures will greatly alter the natural  
304 C fluxes we have here quantified.

## 305 **6. Conclusion**

306 Although the area of the Ucayali's 1984-2019 meander belt represents only a small fraction of  
307 the Amazonian basin area, it significantly contributes to the amount of C that is transferred from  
308 the floodplain forest to the aquatic continuum. The amount of woody C per unit area provided  
309 by floodplain erosion caused by lateral channel erosion is nearly ten-fold higher than that  
310 provided by central Amazon wetlands. Extrapolation of our results suggests that free  
311 meandering white-water rivers may act as major agent in the global C cycle. These findings  
312 point to the importance to quantify the overall contribution of free meandering forested  
313 floodplain rivers worldwide to the global C cycle. In addition to variations in channel migration  
314 rates, different floodplain tree species may show contrasting C-stock potentials and related  
315 forest carbon export rates according to climate zones and biogeographical regions.

## 316 **7. Author contributions**

317 **Romain Wacker:** Conceptualization, Methodology, Formal analysis, Writing- Original draft  
318 preparation. **Dov Corenblit:** Original Idea, Supervision, Conceptualization, Writing- Original  
319 draft preparation. **Frédéric Julien:** Writing - Review & Editing. **Jean-Michel Martinez:**  
320 Writing - Review & Editing. **Johannes Steiger:** Writing - Review & Editing.

## 321 **8. Competing interest statement**

322 The authors have no competing interests to declare.

## 323 **9. Acknowledgements**

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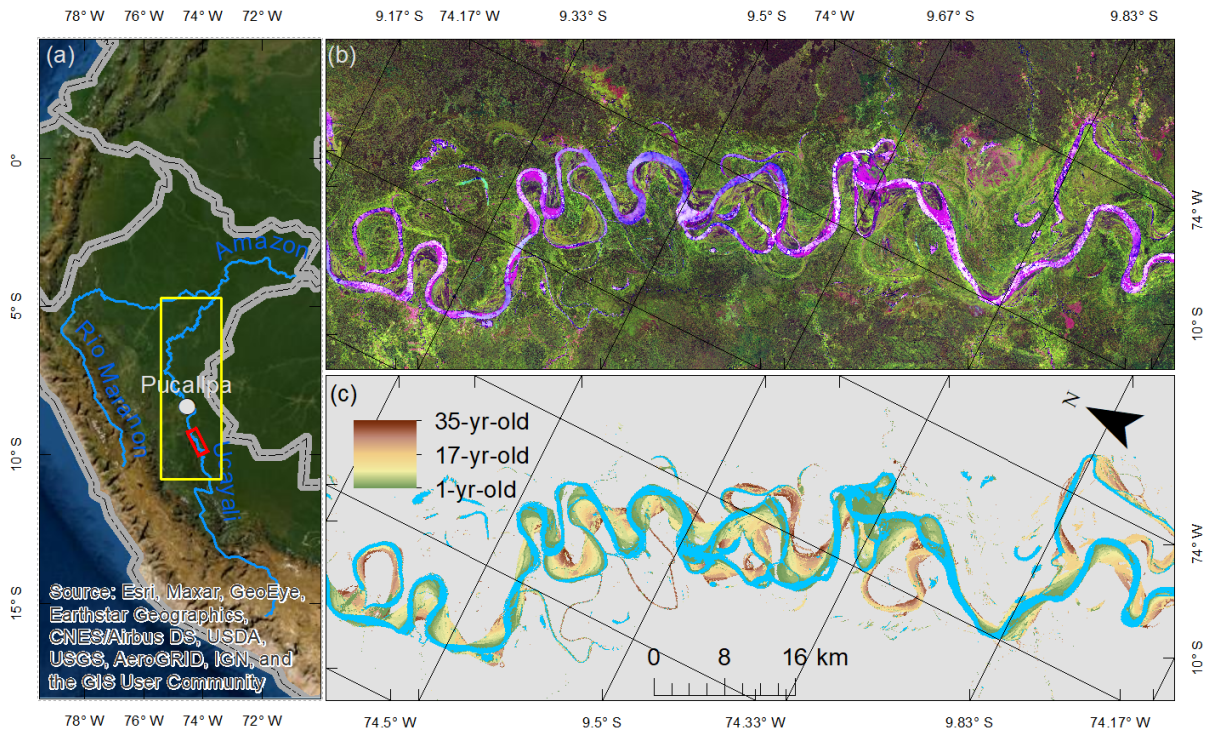
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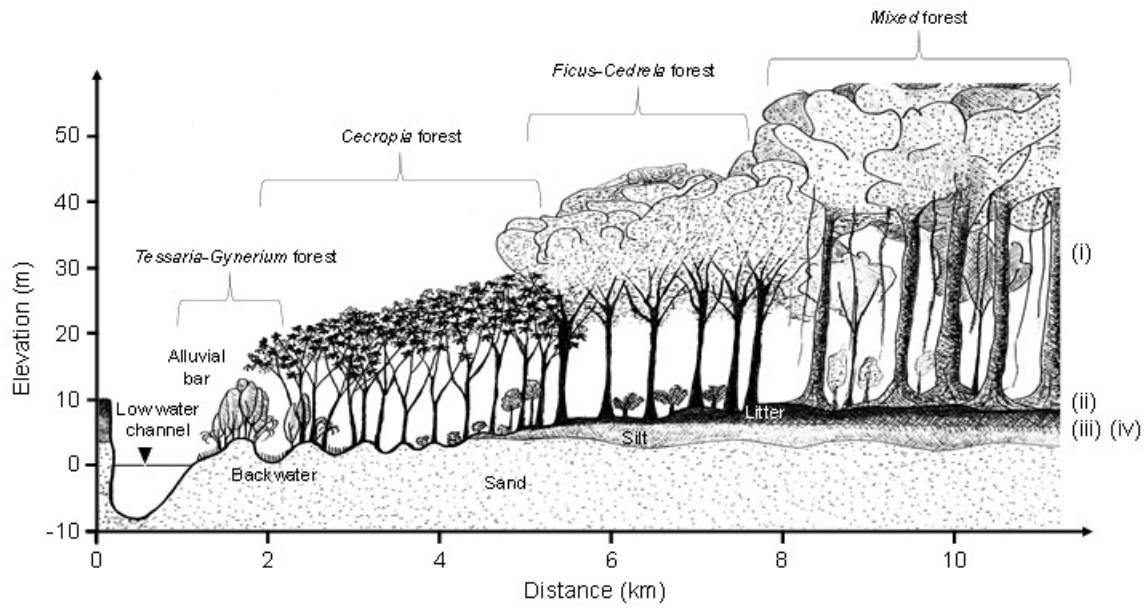
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464  
 465 **Figure 1** The freely meandering Ucayali River in the upper Amazonian region, Peru. **(a)**  
 466 Location map: the yellow rectangle indicates the extent of the study area and the red rectangle  
 467 indicates the extensions of panels (b) and (c), located approximately 120 km upstream of  
 468 Pucallpa, Peru. **(b)** False colour composite satellite image showing the Ucayali meander belt  
 469 extension in light green. This cloud-free satellite Landsat 8 image was obtained through the  
 470 selection of the greenest pixels over the year 2018. The first short wave infra-red satellite band  
 471 was affected to the red colour on screen, the near infra-red band to the green and the red band  
 472 to the blue. **(c)** Floodplain ages range from 1-year (green colour) to 35-year (brown colour)  
 473 within the 1984-2019 meander belt. Blue and grey colours correspond respectively to surface  
 474 water and upland areas formed before 1984 (non-determined ages), respectively.  
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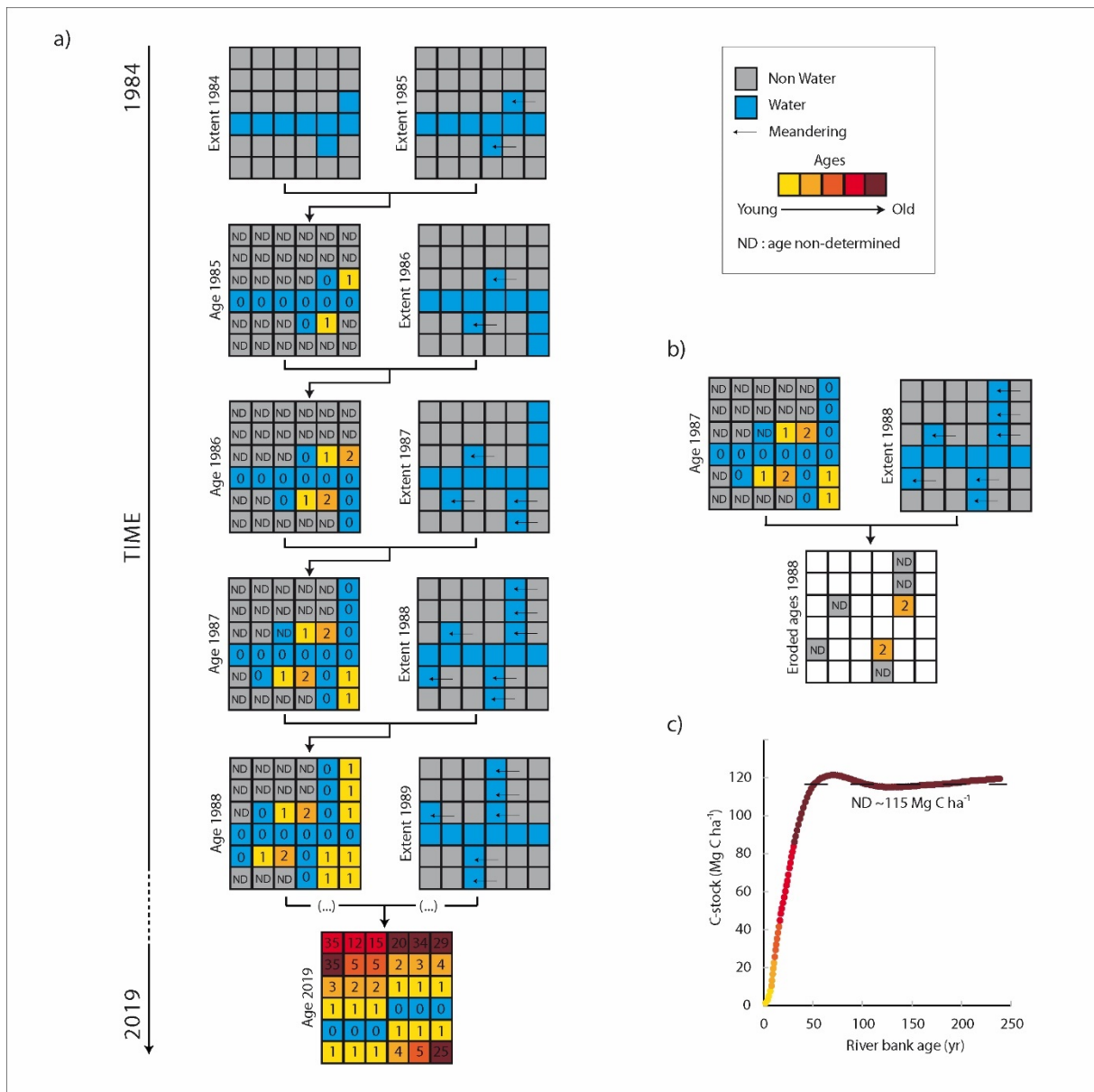


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478 **Figure 2** Simplified model of the floodplain vegetation succession in the study area which  
 479 comprises four main interrelated carbon reservoirs (modified from Salo *et al.*, 1986; Kayranli  
 480 *et al.*, 2010; Stufin *et al.*, 2016): (i) aboveground living terrestrial and seasonally flooded forest  
 481 biomass (trunk, branches and foliage); (ii) aboveground necromass (dead wood and litter); (iii)  
 482 belowground living biomass (roots and micro-organisms); and (iv) total organic matter in the  
 483 soil (decomposed dead organic flora and fauna). The present study focused on the first carbon  
 484 reservoir of the floodplain, i.e. aboveground living terrestrial and seasonally flooded forest  
 485 biomass.

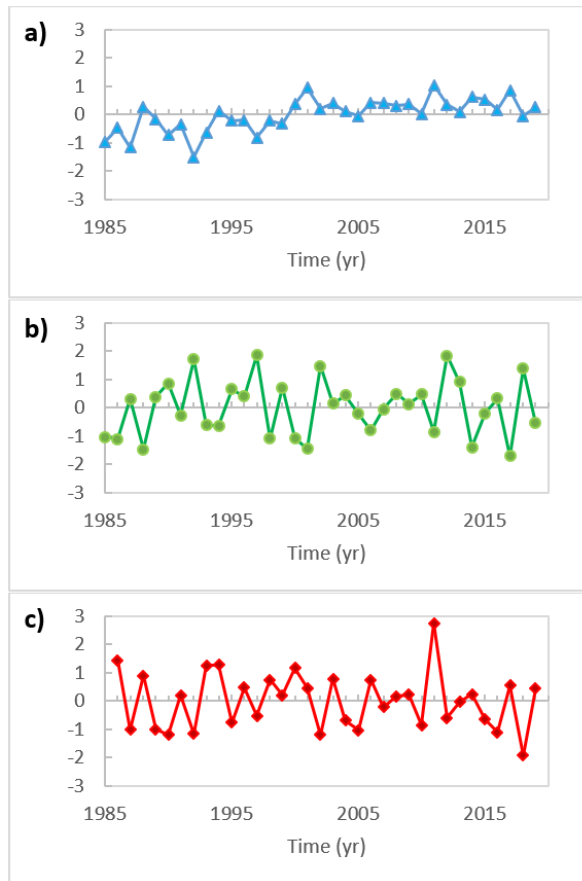
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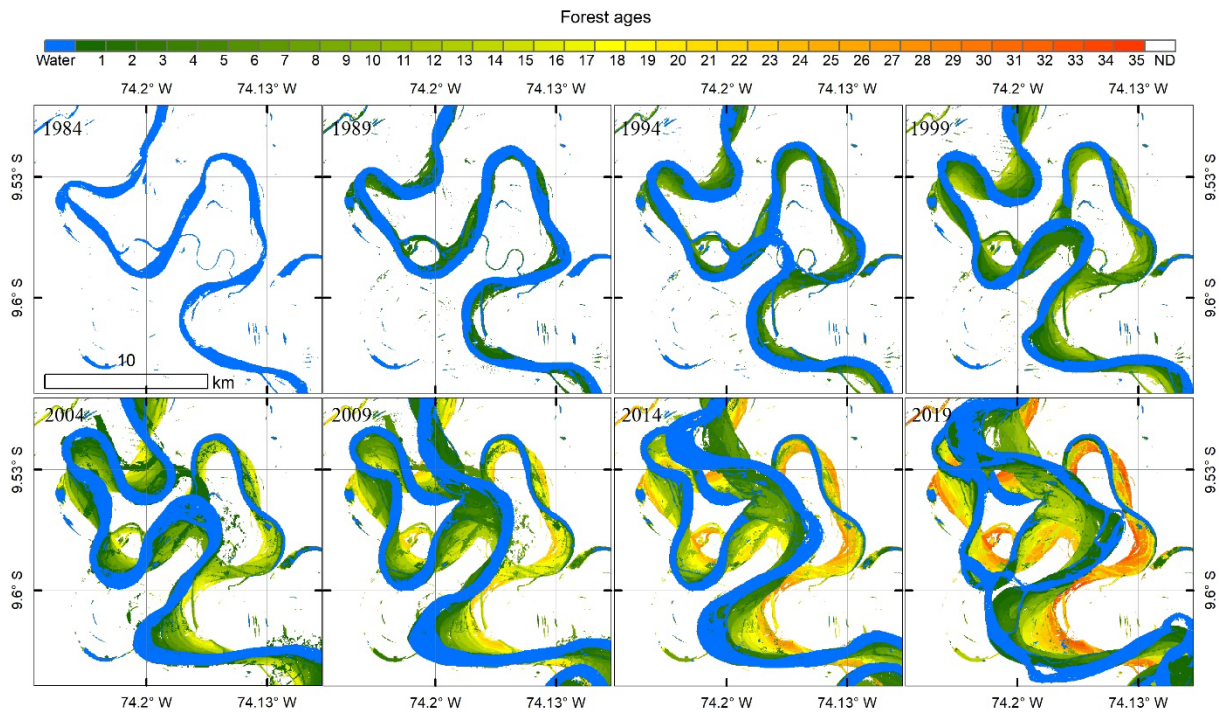
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489 **Figure 3** Conceptual approach used to derive forest above ground carbon stock (C-stock) from  
 490 floodplain area age. **a)** Pixel-by-pixel and year-by-year algorithm used to obtain yearly maps  
 491 of area ages based on the analysis of the yearly water classification history dataset (Pekel *et al.*,  
 492 2016). **b)** Pixel-by-pixel and year-by-year algorithm used to obtain yearly maps of eroded  
 493 floodplain area ages. **c)** Data series used to model and derive C-stocks from floodplain area  
 494 ages (Schöngart and Wittmann, 2010).  
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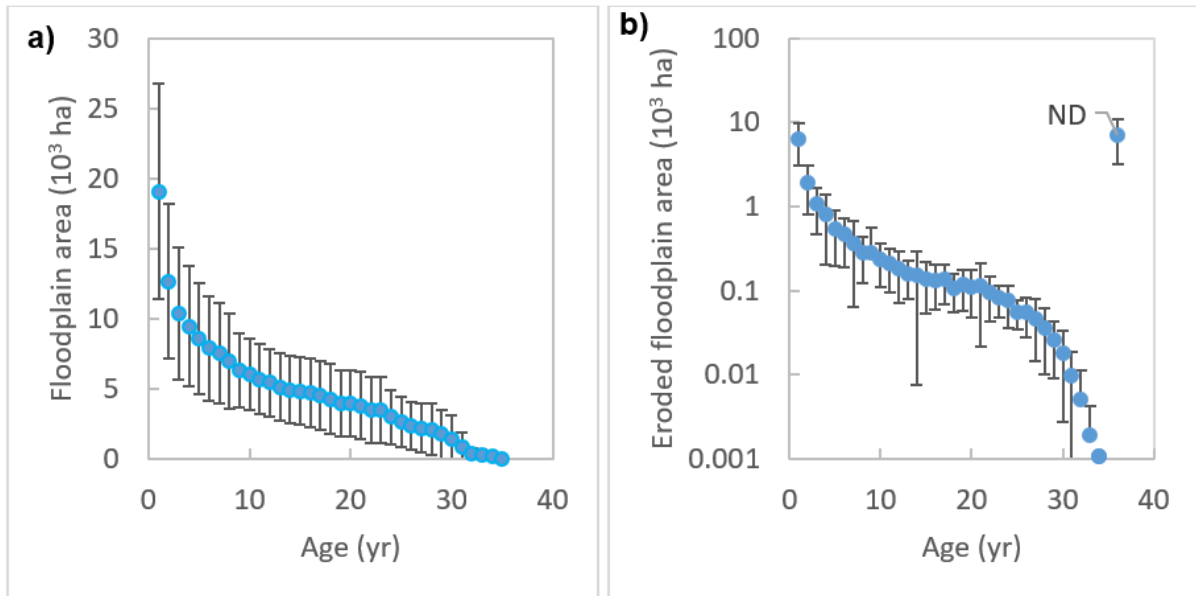
497 **Figure 4** Annual area fluctuations of **a)** water surfaces, **b)** floodplain formation and **c)**  
 498 floodplain erosion between 1984 and 2019. Values are standardized, i.e. the 1984-2019 average  
 499 was subtracted and the result was divided by the 1984-2019 standard deviation.  
 500



501

502 **Figure 5** River meandering and floodplain forest dynamics according to a 5-yr time interval  
 503 between 1984 and 2019 in the vicinity of Sampaya (Peru). Annual maps were created using the  
 504 algorithm described in Fig. 3a. Non-eroded, remaining floodplain and upland forests which  
 505 established before 1984 are indicated as age non-determined (ND; white colour).  
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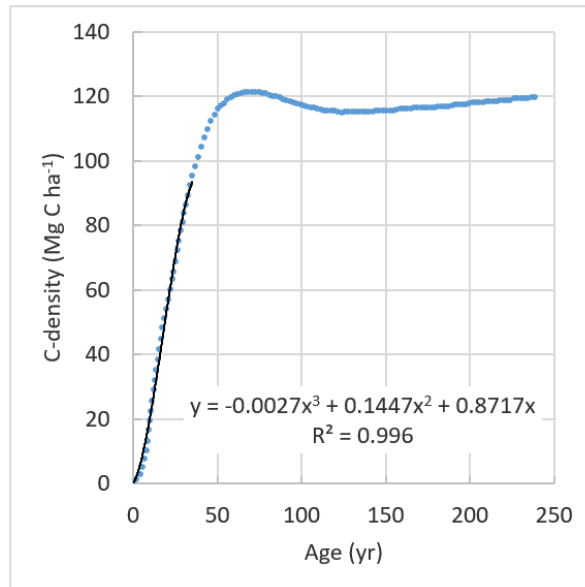


508

509 **Figure 6** Age structure of vegetated floodplain areas observed in the 1984-2019 active meander  
510 belt. **a)** Floodplain areas according to floodplain ages established since 1984. **b)** Eroded  
511 floodplain areas since 1984 according to floodplain ages. Non-determined ages (ND)  
512 corresponding to floodplain or upland areas established before 1984, were considered for  
513 erosion. Together, mean annual erosion accounted for  $19.8 \pm 6.7 \times 10^3 \text{ ha}^{-1} \text{ yr}^{-1}$ . Points and bars  
514 indicate annual mean values for the period 1984-2019 and their standard deviations,  
515 respectively.

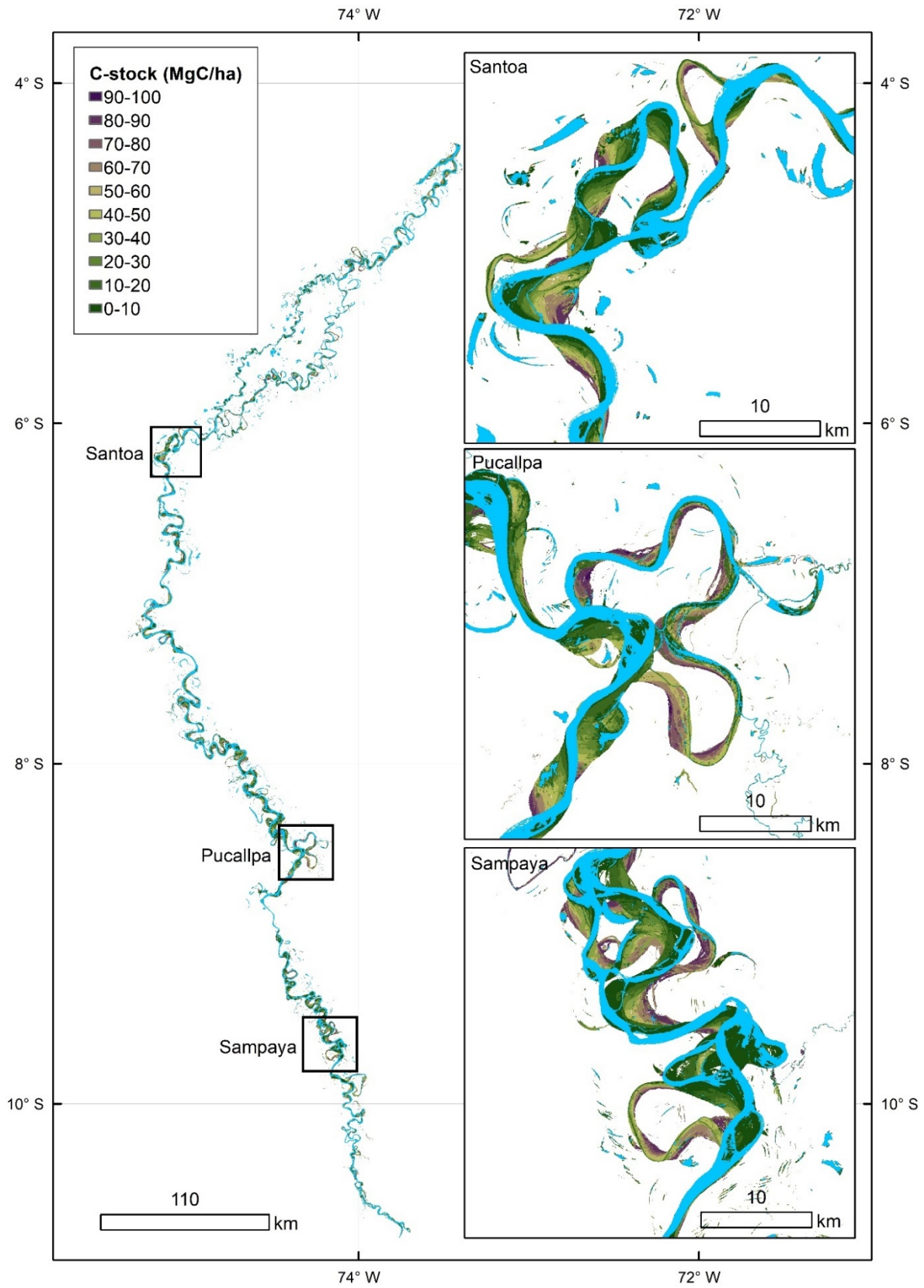


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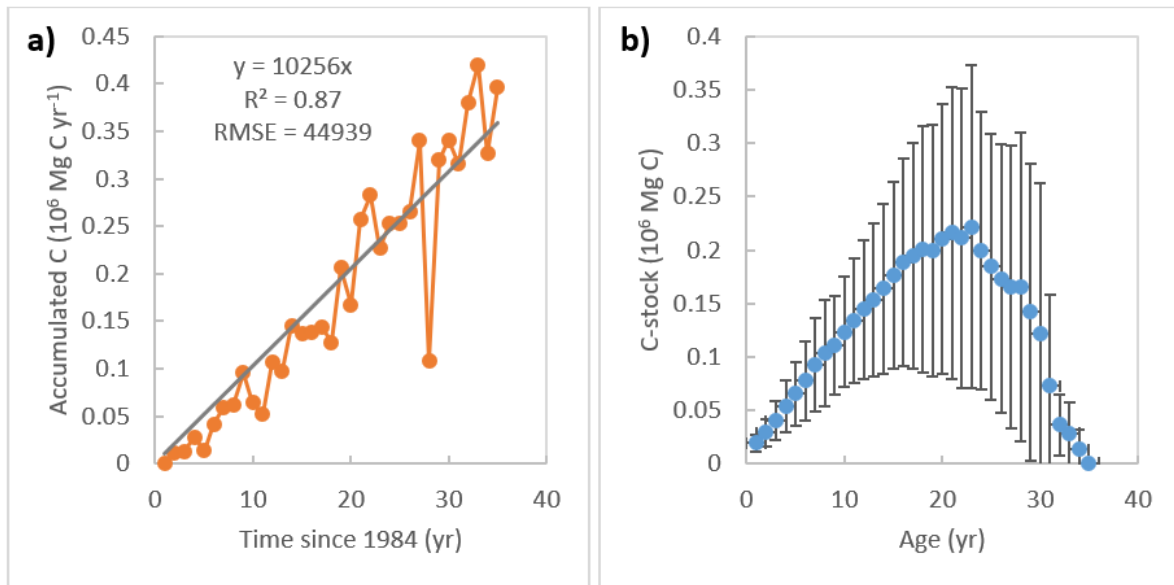
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518 **Figure 7** Model used to derive above-ground forest C-stocks from floodplain forest age. The  
519 model between 1 and 35 years (3rd polynomial; black line) is based on data (dots) published by  
520 Schöngart and Wittman (2010). The data error range is  $\pm 2\%$  (not indicated in the figure).  
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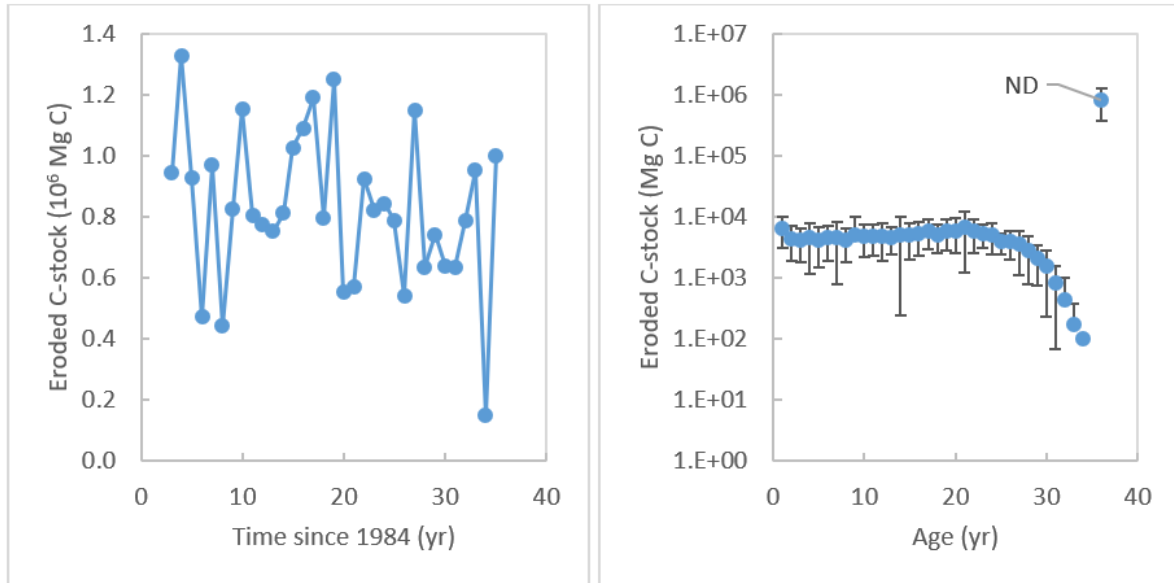
**Figure 8** Above-ground floodplain forest carbon stock (C-stock in  $\text{Mg C ha}^{-1}$ ) in the Ucayali 1984-2019 meander belt. Thirty yearly maps were produced for the 1984-2019 period. This figure shows the map of 2019.



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**Figure 9** Floodplain forest carbon stocks (C-stocks) during the 1984-2019 period in the Ucayali active meander belt. **a)** Annual C accumulation in the floodplain forest established since 1984 and quantified annually until 2019. The black line indicates the annual C accumulation rate as a linear trend of 10256 Mg C yr<sup>-1</sup> ( $R^2 = 0.87$ , p value < 0.01 and RMSE = 44939 Mg C yr<sup>-1</sup>). **b)** Annual C-stock accumulated in the floodplain forest according to the floodplain age established since 1984.

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539 **Figure 10** Erosion of floodplain forest carbon stocks (C-stocks) caused by lateral channel  
540 migration. **a)** Annual C-stocks eroded from the floodplain forest during lateral channel  
541 migration between 1984 and 2019. **b)** Annual C-stock eroded from the floodplain forest during  
542 lateral channel migration according to forest age. ND indicates floodplain and upland forests  
543 established before 1984.  
544