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RESEARCH ARTICLE
10.1029/2023JG007751

Agricultural Land-Use Increases Carbon Yields in Lowland Streams of the Congo Basin

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Key Points:

- Streams draining agricultural land-use in Congo lowlands exhibited higher water and organic carbon yields
- The composition and inferred sources of organic carbon did not differ between forest and agricultural streams
- Low intensity shifting agriculture in Congo lowlands thus exports a high proportion of net primary productivity downstream

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Drake, T. W., Baumgartner, S., Barthel, M., Bauters, M., Alebadwa, S., Akoko, N. B., et al. (2024). Agricultural land-use increases carbon yields in lowland streams of the Congo Basin. *Journal of Geophysical Research: Biogeosciences*, *129*, e2023JG007751. https://doi.org/10.1029/2023JG007751

Received 22 AUG 2023
Accepted 13 FEB 2024

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Abstract As the dominant mode of deforestation in the Congo Basin, shifting agriculture is expected to increase with the projected four-fold population growth for the region by 2,100. To assess how this land-use change will affect the export of carbon (C) to rivers in a typical lowland forest ecosystem, we studied paired watersheds near Kisangani, Democratic Republic of the Congo. Two streams, one draining an intact forest (Forest) and one draining an agricultural landscape (Ag), were gauged, equipped with sensors, and sampled fortnightly for one year. Annual average specific discharge was 1.4 mm d^{-1} (+76%) higher in the Ag compared to the Forest. Average annual dissolved organic C (DOC) and particulate organic C (POC) concentrations were 5.2 mg L^{-1} (+163%) and 1.3 mg L^{-1} (+81%) higher in the Ag stream, which, along with the higher discharge, resulted in 8.3 (+410%) and 2.4 g C m^{-2} yr^{-1} (+97%) larger C yields, respectively. Baseflow dissolved inorganic carbon, carbon dioxide, and methane yields were also higher in the Ag stream. Despite the higher yields of organic C (OC), the composition of OC did not differ significantly. Carbon to nitrogen ratios, along with isotopic signatures, revealed that both streams contained young, semi-degraded organic matter derived from C3 vegetation. Correspondingly, biodegradable DOC (BDOC) proportions did not differ between the streams, although the Ag stream yielded more total BDOC. These results show that agricultural land-use likely exports a greater proportion of Net Primary Productivity (NPP) to aquatic ecosystems, which may affect both C storage in soils and the proportion of gross PP that is ultimately respired.

Plain Language Summary Shifting agriculture, which is the main way forests are cleared in the Congo Basin, is expected to increase as the population grows. To see how this type of deforestation affects the amount of carbon that ends up in rivers, we studied two types of watersheds: one with only forest and one with mostly farms. We measured the water flow and carbon levels in streams draining these watersheds for a year. We found that the stream draining the farmed area had more water and more carbon compared to the forest stream. This means that more carbon from plants and soil was being washed into the farm stream. The carbon in both streams came from similar sources: partially broken-down plants and topsoil that were recently grown or formed, respectively. The farm stream had a bit more carbon that could break down further once it entered the stream. These findings tell us that farming sends more plant matter and carbon into rivers. This could affect how much carbon is stored in the soil and how much goes back into the air.

1. Introduction

Rivers and streams are important conduits for terrestrial-derived carbon (C), transporting and processing significant quantities of net ecosystem production (NEP) and soil-derived carbon dioxide (CO_2) to downstream ecosystems, the atmosphere, and the ocean. As such, rivers are increasingly recognized for their critical role in the global C cycle (Battin et al., 2009, 2023; Cole et al., 2007). Rivers transport dissolved and particulate organic carbon (DOC and POC, respectively) derived from the leaching and mobilization of vegetation, litter, and soils. They also transport dissolved inorganic carbon (DIC), which is composed of heterotrophic and autotrophic respiratory CO_2 and bicarbonate (HCO_3^-) sourced from the weathering of minerals. The flux and composition of

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these different C species within a river catchment is determined by the interplay of climate, topography, and lithology, which in turn control vegetation land-cover and hydrology (Hanley et al., 2013; Raymond et al., 2004).

Human impacts that alter these watershed characteristics (i.e., deforestation and conversion of forest land-cover to croplands) can influence the quantity and composition of C transported to rivers. Croplands and pastures now comprise ~40% of Earth's terrestrial surface, which makes agricultural land-use arguably the largest human impact on Earth (Foley et al., 2005). Ongoing agricultural expansion is particularly rapid in the tropics, which also contain Earth's largest C-rich forests in the Amazon and Congo Basins. In the Congo Basin, deforestation is primarily driven by shifting agriculture (Curtis et al., 2018), a system of smallholder cultivation in which a plot is cleared (often by fire) and cultivated for a short period of time before being abandoned and left fallow. As a result of the dependency of the local population on forests for food and energy, the rate of forest loss in the Congo has risen in lock step with human population (Tyukavina et al., 2018) and stands to increase dramatically with the predicted four-fold population growth in the coming century (Gerland et al., 2014). This scale of land-use change has important consequences for the C cycle of the Congo Basin, particularly via disruption of the forest C sink (Hubau et al., 2020). Moreover, the replacement of forests with croplands will also have downstream effects on the hydrology and transfer of terrestrial C to the aquatic network.

Recent work in the Congo Basin has highlighted the role of deforestation in altering the quantity and composition of C mobilized to rivers and streams. In the montane highlands, the loss of forests was shown to reduce DOC yields but increase the amount of biodegradable, soil-derived C in streams (Drake et al., 2019). In the lowland streams of the western Congo basin, DOC concentrations increased with moderate deforestation and decreased with severe (~77%) forest loss (Drake et al., 2020). Meanwhile, DIC concentrations increased significantly with deforestation (Drake et al., 2020). These studies point to the dramatic effect of land-use conversion on riverine C biogeochemistry in the Congo Basin, however, they did not include the full spectrum of C species (DOC, POC, DIC, CO_2, CH_4) and they did not systematically incorporate discharge into their assessments. Because the type of disturbance can preferentially mobilize one size fraction over another (i.e., particulate vs. dissolved), the fate of OC can depend on its size (i.e., accessibility to microbes, susceptibility to deposition/burial, etc.), the distribution of the carbonate species in DIC can be influenced by pH (and thus organic acidity), and the greenhouse gas warming potential varies dramatically between the C gases, capturing the full spectrum of C species exported by rivers provides a more comprehensive understanding as to the total impact on the C cycle.

To that end, this study monitored high resolution stream water discharge, turbidity, fluorescence of dissolved organic matter, along with fortnightly DOC, POC, DIC, CO_2, and CH_4 concentrations in a paired Congolese lowland forest and nearby agricultural catchment for one year. Using measured and modeled concentrations along with respective discharge measurements, area-normalized fluxes (yields) were generated for each constituent. Additionally, C:N ratios, stable C isotopes, radiocarbon isotopes, and biodegradable DOC (BDOC) were analyzed to ascertain OC sources and reactivity.

2. Methods

2.1. Site Description

The study region was located south of Kisangani, Democratic Republic of Congo (Figure 1). The natural vegetation of this region is lowland tropical forest, which is found inside the Yoko Forest Reserve and in less impacted areas further from Kisangani. These lowland forests are composed of various mixed deciduous broadleaf tree species and stands of monodominant (>60% basal area) *Gilbertodendron dewevrei*. The dominant land-use surrounding Kisangani is shifting agriculture, which typically consists of a mosaic of cleared and planted plots interspersed with fallow areas under various stages of regrowth. In these regions, forests are cut, harvested for their wood, and burned to make way for agriculture. While it can vary, the fallow areas are usually allowed to regrow for 5–10 years and contain small shrubs and young trees, typically *Musanga cecropioides*, of varying ages and sizes. The impacted areas around Kisangani have undergone many cycles of clearing, planting, and fallow over the last century. Crops are a mix of C3 and C4 plants, including cassava, plantains, maize, beans, rice, and groundnuts. While there is some livestock within the agricultural areas, its density is very low, consisting of only a few cows, goats, and chickens per hectare. Given that most farms are smallholder plots practicing subsistence agriculture, there is no import or application of fertilizer or manure to the crops. Likewise, there is no human waste management other than pit latrines. Outside of Kisangani, human population densities are low, rarely exceeding 50 people per square kilometer (https://hub.worldpop.org/geodata/summary?id=45800).

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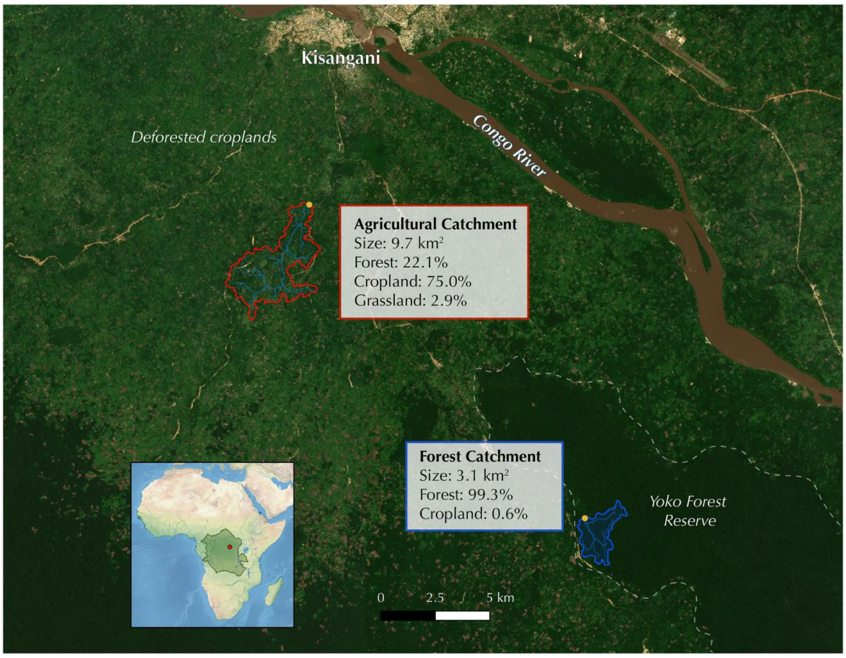

Figure 1. Map of the study catchments south of Kisangani, Democratic Republic of Congo. Agricultural catchment is shown red and forest catchment within the Yoko Forest Reserve is shown in blue. Flume and sampling locations of each catchment are shown as yellow dots. Respective land-cover proportions were derived from the ESA CCI Land Cover data. Study site shown as red dot within the Congo Basin (green outlined area) in the African continent insert.

The two study catchments were selected for their comparable size, representativeness of their respective forest and agricultural (Ag) land-covers, and accessibility from Kisangani (40 and 20 km, respectively). The catchments were delineated using digital elevation models (DEM) derived from the 30m Shuttle Radar Topographic Mission (SRTM; NASA). The forest catchment is 3.1 km^2 in size, has an elevation range of 440–475 m a.s.l., an average slope of 4.3°, and is located entirely within the Yoko Forest Reserve with 99% of the internal area classified as forest. The Ag catchment is closer to Kisangani, has an area of 9.7 km^2, an elevation range of 415–475 m a.s.l., and an average slope of 4°. It drains an area with a mix of croplands (75%), forest (22%), and grassland (3%) that is typical for areas dominated by shifting agriculture in the region. LANDSAT satellite imagery shows that the Ag catchment has been deforested and converted to its current proportion of cropland since at least the late 1980s, while certain areas in the northern side of the catchment were likely cleared much earlier.

2.2. Monitoring, Sampling, and Processing

In order to generate reliable and accurate continuous water discharge measurements, concrete flumes with fixed widths (1.6 and 5 m for the Forest and Ag, respectively) were constructed (Forest flume: 0.2925°N, 25.2951°E; Ag flume: 0.4219°N, 25.1816°E). In the bottom center of the flume channel, a pressure transducer (CS451, Campbell Scientific, USA) was installed and connected to a datalogger (CR1000, Campbell Scientific, UK) to measure water level at 5-min intervals. To obtain a water level versus discharge rating curve, fortnightly discharge was measured manually using a mechanical flowmeter (Model 2030, General Oceanics Inc., USA). In addition to the pressure transducer, probes that measured and internally logged turbidity, fluorescence of dissolved organic matter (fDOM), pH, dissolved oxygen, conductivity, and temperature every 15 min (EXO2 YSI, Xylem, USA) were deployed in the center of each flume. These sensors were factory pre-calibrated and cross-checked to assure comparability of the optical measurements between both sites. Moreover, each probe was equipped with an on-board wiper, which brushed all sensors every 15 min to prevent biofouling. The multisensor probes were deployed on 3 April 2019 at both sites and ran for one complete year at the forest site and until March 9th of 2020 at the Ag site due to security issues.

In addition to the continuous monitoring, fortnightly water samples were collected at both sites to determine dissolved and particulate C concentrations, dissolved inorganic carbon (DIC), dissolved carbon dioxide (pCO$_2$),

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and dissolved methane ($p$$CH_4$). For DOC and POC, raw water samples were taken from the thalweg in acid-leached triple-rinsed 2L HDPE bottles. DIC, CO_2, and CH_4 were sampled by injecting 6 mL of bubble-free river water taken from 0.05 m below the water surface with a syringe into six N_2 flushed, gas-tight exetainers (12 mL, Labco, UK). Prior to sampling and N_2 flushing, three of the exetainers were dosed with 10 μL of 12M HCl (for DIC analysis) and all six exetainers were treated with 50 μL of 50% $ZnCl_2^-$ (to suppress microbial activity; for CO_2 and CH_4 analyses). Because the fortnightly samples tended to occur during baseflow conditions, an autosampler (6,712 Portable Sampler, Teledyne ISCO, USA) equipped with 24 × 1 L PVC bottles was installed at the forest site to capture POC concentrations during storm events. The autosampler was connected to the datalogger and set to trigger when the water level reached 0.175 m, a height selected to exceed the normal range of baseflow water level as determined prior to the monitoring period. Each of the 24 bottles was pre-poisoned with 5 mL of 50% $ZnCl_2$ to minimize biological activity. Unfortunately, the autosampler was unable to be deployed at the Ag site due to security issues.

After collection, samples were processed and stored in a laboratory at the University of Kisangani. Water samples were filtered through pre-combusted (450°C, >5°h) and pre-weighed 0.7 μm glass fiber filters (Whatman GF/F) using a vacuum pump. The amount of water passed through each filter was determined using a graduated cylinder and recorded. Filters were then sealed in plastic cases and frozen prior to transport to Zurich for POC analyses. Filtrate was collected in acid-leached HDPE bottles for DOC analyses and six pre-combusted exetainer vials for biodegradable DOC (BDOC) incubations. DOC samples and three of the exetainers (timepoint 0, triplicate) were immediately acidified to pH 2 with 12N HCl. After 28 days, the remaining three exetainers were acidified (timepoint 28, triplicate). DOC samples were frozen prior to transport to Zurich for analyses.

2.3. Carbon Analyses

DOC and total dissolved nitrogen (TDN) concentrations were measured on the thawed filtered water samples via high-temperature catalytic oxidation on a Shimadzu TOC-L total organic carbon analyzer equipped with a TNM-1 module using established methodology (Drake et al., 2018). Stable ($\delta^{13}C$) and radiocarbon (^{14}C contents) isotopic signatures of DOC were determined via isotope ratio mass spectrometry (0.1‰ precision) and accelerator mass spectrometry, respectively, at the Laboratory of Ion Beam Physics (LIP) of ETH Zurich using established procedures (Mcintyre et al., 2017). Due to sample volume limitations, radiocarbon was prioritized over $\delta^{13}C$, which was only measured on nine samples.

After transport to Zurich, the POC filters were thawed and dried at 60°C for 48 hr. Total suspended solids (TSS) concentrations were determined by dividing the difference in weight between the pre-weighed filters and the dried filter after filtration by the amount of water filtered. POC concentrations were determined by feeding the whole filter to an elemental analyzer (Automated Nitrogen Carbon Analyzer, SerCon; Crewe, UK). Mole fractions of DIC, dissolved CO_2, and dissolved CH_4 were measured on equilibrated gas headspaces of the exetainers via gas chromatography (456-GC, Scion Instruments, UK) using a suite of standards that spanned the expected range of concentrations. Dissolved concentrations were calculated using headspace mole fractions and exetainer headspace/water volume ratios according to Henry's law.

2.4. Modeled Carbon Concentration and Yields

Prior to modeling the full timeseries of DOC concentration, fDOM measurements were corrected for attenuation using standardized methods (Supplemental Methods). Due to security issues at the Agricultural site, storm event (i.e., high flow) concentrations were not able to be measured. Thus, for both sites, linear regressions of DOC and POC concentrations versus the YSI EXO2 probe data (fDOM and turbidity, respectively) were used to model 5-min interval DOC and POC concentrations ($r^2 = 0.80$, $p < 0.0001$ and $r^2 = 0.76$, $p < 0.0001$ for DOC and POC, respectively; Figure S1 in Supporting Information S1). Given the same calibration settings for both YSI probes, the overlap in DOC concentrations (Figure S1a in Supporting Information S1), and the similar %POC to TSS ratio of the baseflow samples between the Agricultural and Forest sites (Figure S2 in Supporting Information S1), the use of the combined Ag and Forest linear regressions for these models is justified. Nevertheless, some uncertainty in the modeled Ag POC concentration is generated by extrapolating the relationship observed in the Forest site. Carbon yields were calculated by multiplying the modeled concentrations by discharge and dividing by the respective watershed area. All sampling methods, sampling frequency, number of measurements, and underlying assumptions are summarized in Table S1 in Supporting Information S1.

To contextualize and compare the yields of OC from the two catchments, average Net Primary Productivity (NPP) estimates were generated in QGIS for each catchment area using 1-year MODIS Terra satellite NPP raster data for 2018 and 2020 (2019 data is missing for the Kisangani area) and the DEM-derived catchment boundaries. The MODIS NPP estimate is derived via a regression between estimated Absorbed Photosynthetically Active Radiation and estimated meteorology, then scaled according to 10 land cover types globally (https://modis.gsfc.nasa.gov/data/dataprod/mod17.php). As such, this NPP estimate is inherently prone to inaccuracy and should be considered as only a rough approximation of true NPP.

3. Results and Discussion

3.1. Hydrologic Setting

For the year following 4 April 2019, the total annual rainfall for the study site was 2,042 mm, which is typical for the lowlands of the Congo Basin (NASA Global Precipitation Monitoring Mission). Rainfall was relatively consistent across the year, with a period of larger events beginning at the end of September (Day 170; Figure 2).

Given the larger catchment size, the annual average water discharge was consistently higher at the Ag site (0.361 $m^3 s^{-1}$) compared to the Forest site (0.065 $m^3 s^{-1}$). The average specific discharge, which is normalized to the catchment area, was still 76% higher at the Ag site (3.20 mm d^{-1}) compared to the Forest (1.82 mm d^{-1}; Figure 2). This is likely due to lower rates of evapotranspiration and less infiltration into the soil in the Ag catchment compared to the Forest, which results in a higher proportion of rainfall available as runoff. Similar reductions in evapotranspiration have led to higher specific discharges in deforested catchments of the Amazon (Coe et al., 2009; Coe et al., 2011). Using the annual average specific discharge for the Forest (664 mm yr^{-1}) and Ag (1,167 mm yr^{-1}) along with the annual rainfall (2,042 mm), the runoff coefficients for each catchment could be calculated (0.33 and 0.57, respectively). Similar increases in runoff coefficients with land-use have been observed in impacted (i.e., deforested) catchments of the Amazon (Machado et al., 2022).

Water temperature was on average 0.48°C warmer and exhibited a larger range in the Ag stream compared to the forest stream (Figure S3a in Supporting Information S1). The lower proportion of forest cover and thus lower shading in the Ag stream likely allowed for higher solar radiation, slightly warmer temperatures, and more extreme values. The same pattern of higher temperatures in deforested catchments was observed in other lowland streams of western Congo, although the differences were more pronounced (+3.3°C; Drake et al., 2020). Water in the Ag stream was also more acidic (average pH was 0.47 units lower than the forest; Figure S3b in Supporting Information S1) and less saturated in dissolved oxygen (12% lower; Figure S3c in Supporting Information S1). These results likely point to higher rates of respiration (i.e., more oxygen consumption) and higher concentrations of carbon dioxide (see next section), which forms carbonic acid when dissolved and thus lowers pH depending on background alkalinity.

3.2. Carbon Species Concentrations

Average DOC concentrations (±SD) were 3.2 ± 1.3 and 8.4 ± 2.3 mg L^{-1} for the Forest and Ag sites, respectively (Figure 3a). DOC concentrations were thus significantly higher for the Ag site compared to the Forest site (+5.2 mg L^{-1} or 163% increase) but exhibited a similar range of observed values (2.8–28 mg L^{-1} compared to 1.7–26 mg L^{-1}; Figure 3a). The average concentration difference of DOC was also reflected in fDOM (a proxy for DOC, see methods), which was generally higher in the Ag site (Figure S4 in Supporting Information S1). Both the Forest and Ag stream exhibited an increase in fDOM with discharge, indicating a mobilization response, however, fDOM in the Ag site increased more per unit specific discharge (Figure S4 in Supporting Information S1). This (+163%) difference in average DOC concentration is slightly higher than the difference observed in a moderately deforested lowland catchment in the western Congo Basin (+136%; Drake et al., 2020) but contrasted with the ~55% lower DOC observed in heavily deforested catchments of Eastern Congo, where soil degradation is higher (Drake et al., 2019). Previous studies on small tropical catchments in the Amazon Basin and Central America have shown both higher and lower in DOC concentrations with agricultural land-use (Gücker et al., 2016). The mechanisms that drive this variable effect of land-use on DOC concentrations in tropical streams remain unclear, given that agricultural intensity, water yield, soil degradation, riparian disturbance, autotrophic production of DOC, and anthropogenic inputs can all vary substantially and interact to elevate or dilute DOC concentrations. So far, the work from this study and Eastern and western Congo suggests that DOC concentrations in the Congo vary inversely with the level of soil degradation.

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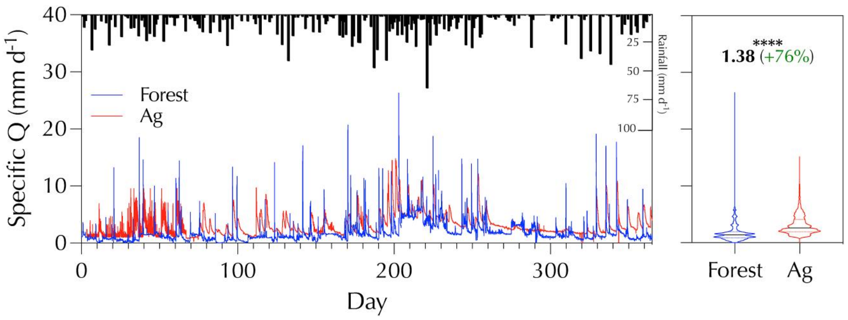

Figure 2. Specific discharge time series for Forest (blue) and Agricultural (Ag, red) streams shown with NASA GPM satellite-derived daily rainfall for the region (black bars). Day 1 is 4 April 2019. Right panel shows the violin plots for all data points in the time series, along with the p-value summary (stars) from the unpaired *t*-test, the average difference (in mm d^{-1}) in bold, and the percent difference between Forest and Agriculture.

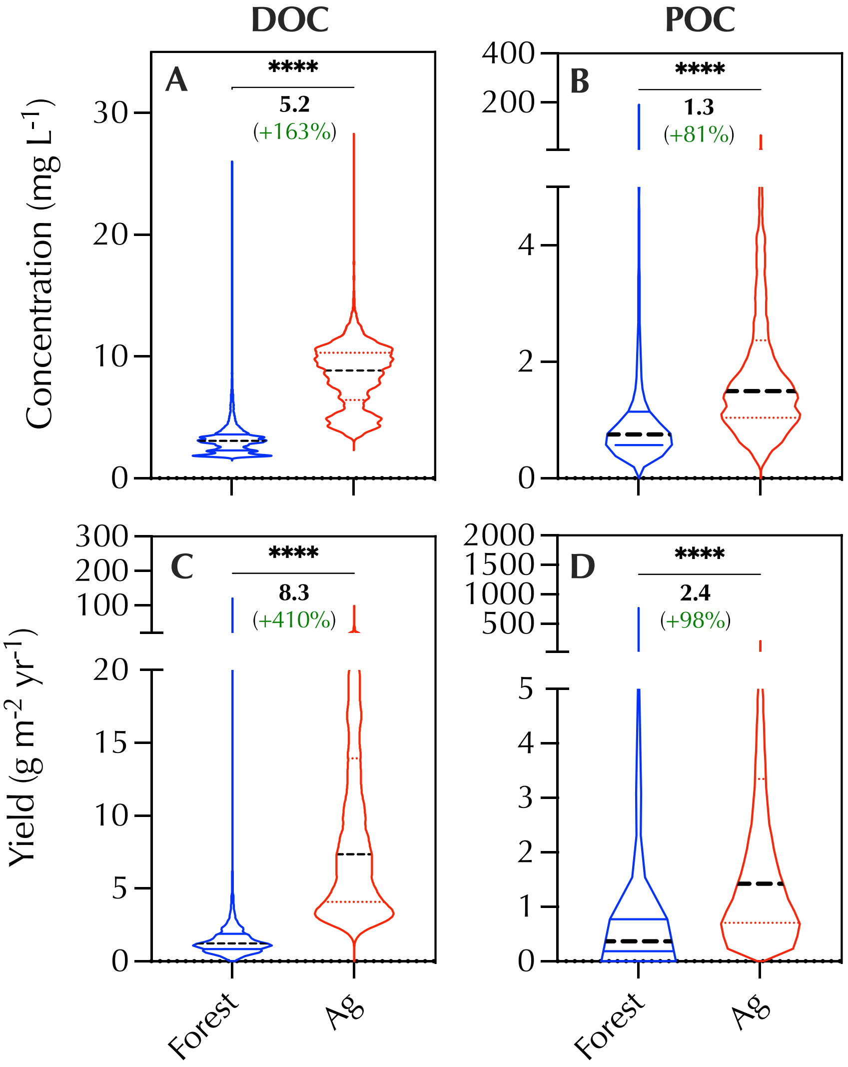

Figure 3. Violin plots of dissolved organic carbon and particulate organic carbon concentrations (a and b, respectively) and yields (c and d, respectively) for the Forest (blue) and Agricultural (Ag, red) streams. For each panel, the Forest versus Agricultural unpaired *t*-test p-value summary (stars), average difference, and the percent difference are shown.

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Average POC concentrations were 1.6 ± 3.9 and 2.9 ± 5.6 mg L^{-1} for the Forest and Ag sites, respectively (Figure 3b). Thus, POC concentrations were also significantly higher in the Ag site, though the difference was less than for DOC (+1.3 mg L^{-1} or 81%; Figure 3b). Interestingly, the maximum POC concentration was higher in the Forest site (191 compared to 65 mg L^{-1}), perhaps due to the smaller catchment size and thus flashier hydrograph, which is indicated by the higher maximum specific Q (Figure 2). Previous research on the TSS concentrations of the Forest stream showed that sediment concentrations increased with discharge and exhibited clockwise hysteresis, caused by the quick flushing of surface material during the rising limb followed by a depletion of source material during the falling limb (Baumgartner et al., 2022). Both the Ag and Forest streams exhibited similar turbidity increases with discharge (Figure S5 in Supporting Information S1), indicating similar sediment mobilization dynamics within the two catchments. Previous research in small tropical watersheds has also shown higher POC concentrations (ranging from +11 to 475%) in agricultural land-uses (Bass et al., 2014; Neill et al., 2001; Thomas et al., 2004). These studies suggested that the higher concentrations of POC observed in the agricultural streams was a result of soil destabilization.

For DIC, CO_2, and CH_4 concentrations, it was not possible to model annual averages that included storm events (see Figure S6 in Supporting Information S1 for hydrograph with sampling points), so only the average "baseflow" concentrations are presented (Figure 4). Average DIC concentrations did not differ between the two streams, while the Ag stream exhibited slightly higher CO_2 concentrations (difference was not significant) and significantly higher CH_4 concentrations (Figures 4a–4c, respectively). Previous studies in both the western lowlands and eastern highlands of Congo observed higher DIC and CO_2 in agricultural streams, attributing the differences to enhanced rock weathering and higher microbial respiration (Drake et al., 2019, 2020). Other work in tropical Australia, however, showed that DIC concentrations in forested and agricultural catchments did not differ and that DIC concentrations were relatively unresponsive to rain events (Bass et al., 2014). Although variation in riverine DIC and CO_2 concentrations can result from a multitude of factors, the results from this study suggest that the rates of rock weathering and/or microbial respiration in the Forest and Ag catchments are yet comparable. In contrast to the similar DIC and CO_2 concentrations, the elevated CH_4 in the Ag stream suggests higher rates of methanogenesis, perhaps resulting from the increased sediment load and possible anoxia within the streambed. Indeed, the Ag stream was less saturated in DO (Figure S3c in Supporting Information S1) and the streambed was qualitatively more blanketed with sediment and had fewer exposed rocks than the Forest site. CH_4 concentration data from agricultural streams in the tropics are scarce. In a sugarcane-dominated catchment of Brazil, streamwater CH_4 concentrations were lower compared to forest, which was attributed to the lower OC loading from the agricultural land-use (i.e., lower DOC and POC inputs; Taniwaki et al., 2022). In this study, the higher relative OC loading combined with the higher probability of anoxia within the streambed of the Ag site likely explains the difference from the study in Brazil.

3.3. Carbon Yields

Carbon yields, which normalize C fluxes to catchment areas, allow for direct comparison of C losses between catchments of different sizes. For this study, average annual carbon yields were universally higher in the Ag stream compared to the Forest (Figures 3 and 4). Annual average DOC yields were 2.0 ± 3.9 and 10.3 ± 8.9 g m^{-2} yr^{-1} for the Forest and Ag sites, respectively (Figure 3c). Annual average POC yields were 2.5 ± 15.5 and 4.9 ± 13.2 g m^{-2} yr^{-1} for the Forest and Ag sites, respectively (Figure 3d). These results show that the yields of DOC and POC were 410% and 98% higher in the Ag stream, respectively. These yield estimates are subject to high standard deviations as a result of the large ranges exhibited by both sites. As with concentrations and discharge, the Forest stream exhibited a larger range of C yields for both DOC and POC, which is expected of a smaller catchment with a flashier discharge response. Interestingly, the observed higher Ag OC yields appear to be driven primarily by the higher concentrations (which were 163% and 181% higher in the Ag stream for DOC and POC, respectively), while the higher water yield played a roughly equal or lesser role (only 76% larger in the Ag stream). This suggests that OC in the Ag catchment is more readily dissolved or mobilized and potentially less source-limited (i.e., more abundant) compared to the Forest. A possible explanation for this is that the Ag catchment experiences simultaneously higher rate of soil disturbance due to tillage and higher production of plant detritus via both slash and burn and crop harvesting.

In addition to exhibiting higher yields of both DOC and POC, agricultural land-use also exhibited different proportions of total OC yielded in the dissolved or particulate phases; DOC:TOC yields were higher (68 compared to 45%) and POC:TOC yields were lower (32 compared to 55%). This finding suggests that, at the

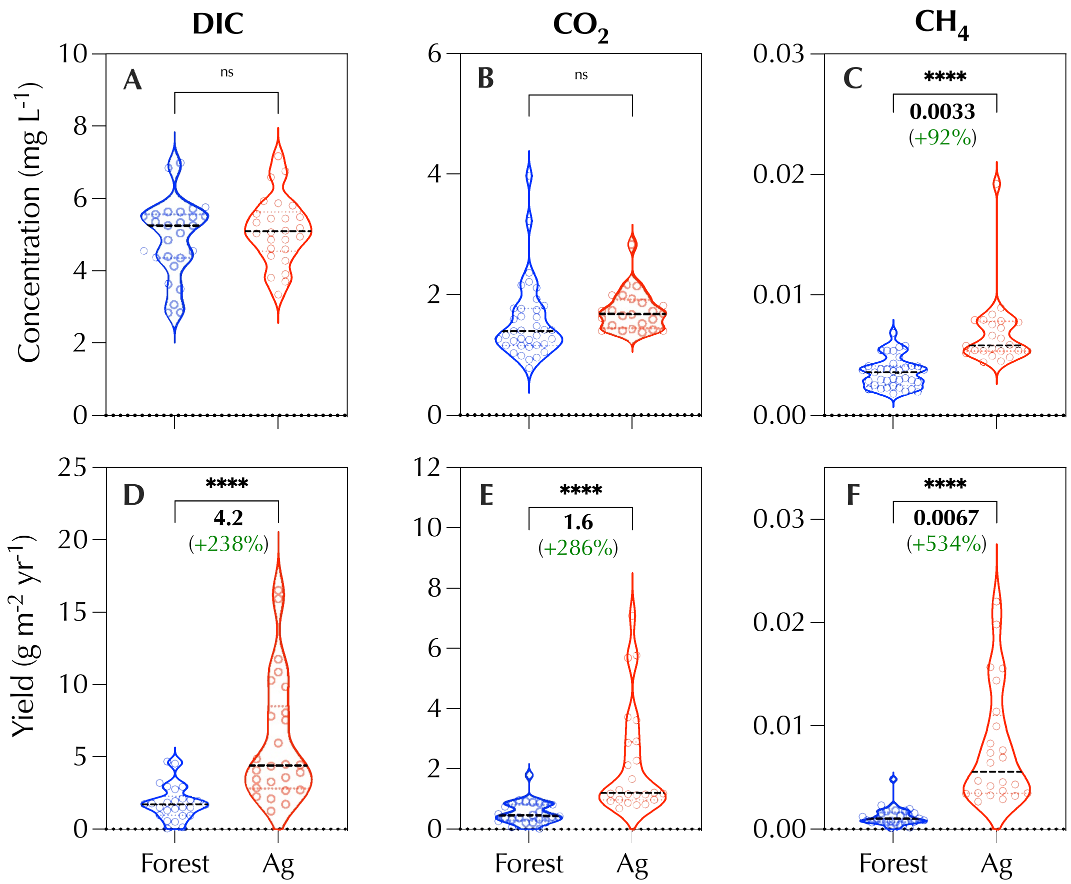

Figure 4. Violin plots of baseflow dissolved inorganic carbon, carbon dioxide, and methane concentrations (a–c, respectively) and yields (d–f), respectively) for the Forest (blue) and Agricultural (Ag, red) streams. For each panel, the Forest versus Agricultural unpaired *t*-test p-value summary (stars), average difference, and the percent difference are shown. Non-significant differences are denoted with a "ns".

catchment level, lowland agricultural land-use enhances the leaching and dissolution of soil and plant organic matter relatively *more* than it increases sediment transport to the river. Indeed, fDOM, a proxy for DOC, was found to increase more per unit discharge in the Ag stream (Figure S4 in Supporting Information S1) while turbidity, a proxy for POC, exhibited a nearly identical response in the two sites (Figure S5 in Supporting Information S1). This observation may be explained by the overall flat topography in the lowlands and the relatively high proportion of intact forest within the riparian areas of the Ag stream, both of which likely serve to buffer sediment erosion into the stream and thus attenuate the effect of land-use on POC mobilization relative to DOC. Moreover, if the stock of riparian C is similar between the two sites, the higher water yield (i.e., higher frequency of riparian flooding and increased contact with riparian soils) in the Ag stream might be expected to preferentially increase DOC concentrations and yields.

The average DOC yield for the Forest site (2.0 g m^{-2} yr^{-1}) was lower than other large tropical rivers (i.e., Amazon 4.4, Congo 3.4, Orinoco 4.5, and Ruki 3.4 g m^{-2} yr^{-1}; Raymond & Spencer, 2015) and tropical montane streams in Puerto Rico, northern Australia, Guadeloupe, and Costa Rica (3.28–9.38, 2.34, 1.9–8.6, and 1.90–4.31 g m^{-2} yr^{-1}; respectively; Bass et al., 2011; Lloret et al., 2013; McDowell & Asbury, 1994; Newbold et al., 1995). However, the DOC yield compared well to other natural, non-montane tropical streams in Kenya (0.39 g m^2 yr^{-1}; Recha et al., 2013) and in the Rio das Mortes (0.05–2.66 g m^{-2} yr^{-1}; Gücker et al., 2016), Central Amazon (1.17–9.02, 3.15 g m^{-2} yr^{-1}; Johnson et al., 2006; McClain et al., 1997) and Cerrado regions (1.26–3.15 g m^{-2} yr^{-1}; Markewitz et al., 2006) of Brazil. The lower DOC yields observed in the Forest stream of this study compared to the larger rivers and more mountainous streams draining volcanic soils (in Puerto Rico, Guadeloupe, and Costa Rica) is likely explained by the relative lack of wetlands and the absence of fertile, OC-rich volcanic soils, respectively. The average annual POC yield from the Forest site in this study (2.5 g m^{-2} yr^{-1})

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was somewhat higher than the few reported values from other non-montane tropical streams, such as those in the central Amazon (<0.001 and 0.89–1.55 g m^{-2} yr^{-1}; Neu et al., 2011; Waterloo et al., 2006), southern Amazon (1.76 g m^{-2} yr^{-1}; Johnson et al., 2006), and Kenya (0.394 g m^{-2} yr^{-1}; Recha et al., 2013).

Few studies have reported the effects of agricultural land-use on C export, as opposed to concentrations, from tropical streams. In Kenya, agricultural land-use led to higher yields of both DOC and POC to headwater streams by a range of 77%–153% and 68%–168%, respectively, depending on the time since conversion (Recha et al., 2013). In agricultural catchments of the Rio das Mortes basin in Brazil, median DOC yield was 213% higher (Gücker et al., 2016). In other Amazonian catchments in both lowland forests and the Cerrado region, DOC export in pastured land-use was 320% and 120% higher, respectively, compared to native vegetation (Nóbrega et al., 2018). Overall, the results of this study are consistent with these findings from tropical regions outside of the Congo Basin and highlight agricultural land-use as a driver of increased OC export. The drivers of this increase, however, may vary from higher water yields to higher rates of mobilization (i.e., higher concentrations). For example, in the Rio das Mortes basin, the higher DOC yields were due solely to the higher specific discharge, whereas in this study they resulted from both higher discharge and higher concentration. Disambiguating the drivers for these differences remains an important task for future studies since they, along with the projected changes in land-cover and climate, are bound to vary regionally. Nevertheless, it is so far clear that agricultural land-use enhances the terrestrial to aquatic transport of carbon in tropical systems.

3.4. OC Composition and DOC Lability

Baseflow DOM carbon to nitrogen (C:N) ratios ranged from 4.2 to 33.3 and 5.9 to 26.7 for the Forest and Ag sites, respectively (Figure 5a). Average values (±SD) were 12.2 ± 6.2 and 13.3 ± 4.9 for the Forest and Ag sites and did not differ significantly from each other. POM C:N values exhibited a much smaller range, with values from 10.4 to 13.7 and 9.8 to 12.3 for the Forest and Ag sites, respectively (Figure 5b). Average POM C:N values were overall quite similar to DOM, with values of 12.1 ± 0.9 and 11.5 ± 0.6 for the Forest and Ag sites, respectively. The average value of the Ag site was thus 0.62 lower than the Forest and was significantly different ($p = 0.008$).

Baseflow δ^{13}C-DOC values were only measured on nine samples, but they exhibited consistent values. Mean values were −30.5 ± 0.8 and −31.1 ± 1.2‰ for the Forest and Ag sites, respectively (Figure 5c). Mean δ^{13}C-POC values were similar to DOC, with values of −30.2 ± 0.9 and −30.0 ± 0.7 for the Forest and Ag sites, respectively (Figure 6d). For both DOC and POC, there was no significant difference between mean values for the Forest and Ag sites (Figures 5c and 5d). The average fraction modern (F_{mod}) values of DOC were 0.99 ± 0.05 and 1.00 ± 0.13 for the Forest and Ag sites, respectively, with no significant difference between the sites (Figure 5e). Although most values fell within the same modern range (0.86–1.1), the Ag site had one old (low F_{mod}) value (0.41).

Collectively, the C:N and isotopic results indicate that the OC in both streams is primarily composed of topsoil and litter derived from C3 plants (mean δ^{13}C values of −30‰) that was recently photosynthesized (high F_{mod}). The relatively low C:N values for OC observed in the river compared to soil and litter (∼13 and ∼20, respectively; Baumgartner et al., 2022) could have resulted due to either in-stream decomposition or preferential mobilization of more decomposed (low C:N) material compared to fresher (high C:N) vegetation. The short residence time and thus limited potential for decomposition in these low-order streams, along with the observation that smaller and thus potentially more mobile organic compounds tend to be enriched in N (such as amino acids and microbial necromass; Drake et al., 2019; Wagner et al., 2015), may point to the latter process. Nevertheless, the export of recent C3-derived OC is typical of lowland forest landscapes that are dominated by C3 vegetation and have low erosion rates (Baumgartner et al., 2022; Mayorga et al., 2005). These results contrast with those from Eastern Congo that showed older and more ^{13}C enriched DOC in streams draining deforested croplands (Drake et al., 2019). This difference is likely explained by the significantly steeper topography and higher rates of soil erosion in the Eastern highlands, which has already removed the topsoil and exposed deeper subsoil. Nevertheless, the striking similarity in OC sources between the two streams in this study is an interesting result, especially given the significantly higher OC yields exhibited by the Ag stream. It is important to note that these compositional data are derived from samples taken during baseflow conditions, which may not reflect the same source of OC exported by the streams during stormflow. However, at least for the forest site, C:N ratios for POC did not significantly differ during stormflow (Figure S7 in Supporting Information S1), despite exhibiting a larger range and a higher %POC content (Figure S2 in Supporting Information S1).

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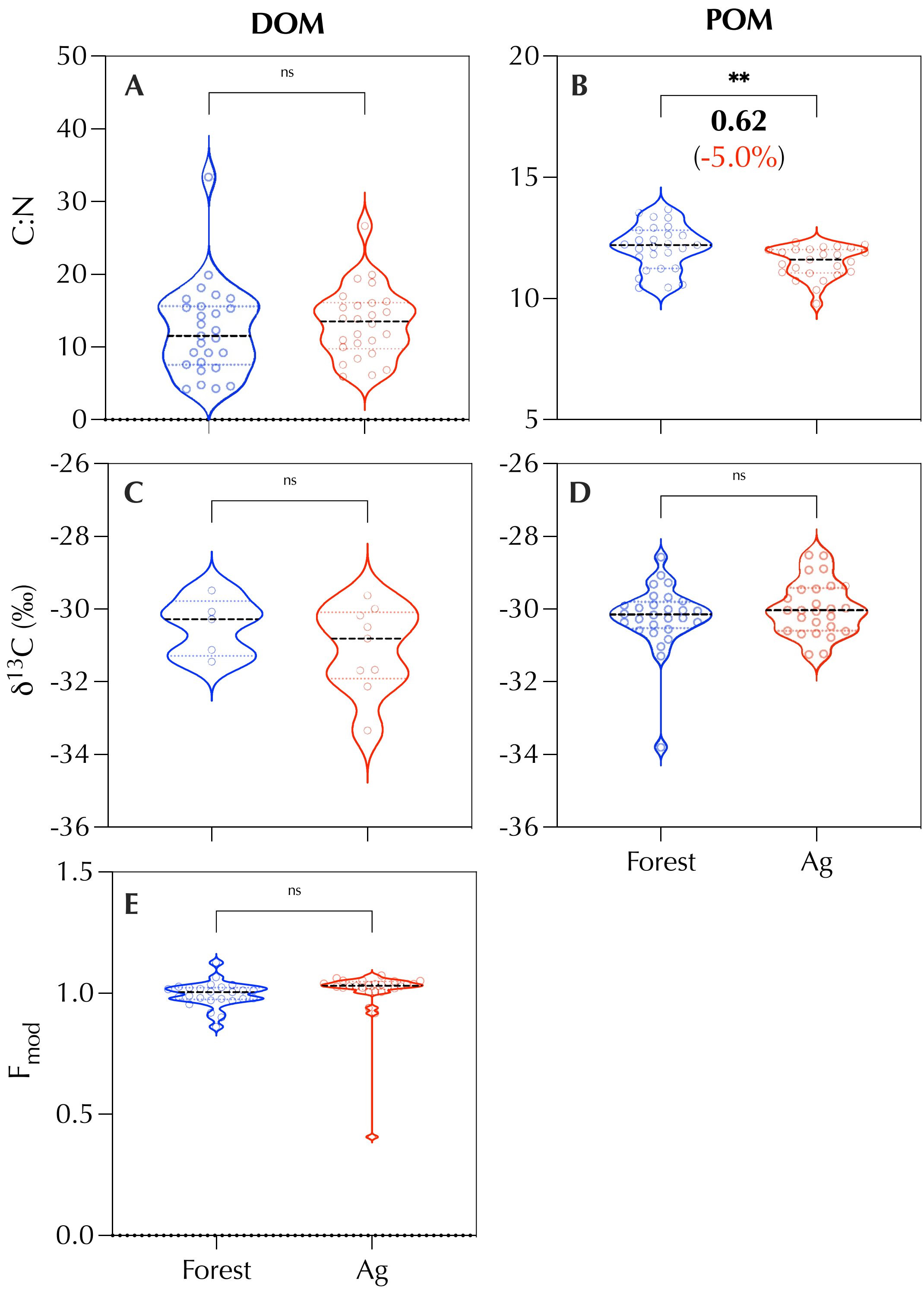

Figure 5. Violin plots of C:N ratios (a) and (b), ^{13}C isotopic signatures (c) and (d), and fraction modern (e) for dissolved organic matter (left panels) and particulate organic matter (right panels) sampled from the Forest (blue) and Agricultural (Ag, red) sites during baseflow conditions. For each panel, the Forest versus Agricultural unpaired *t*-test p-value summary (stars) and average difference are shown. Non-significant differences are denoted with a "ns".

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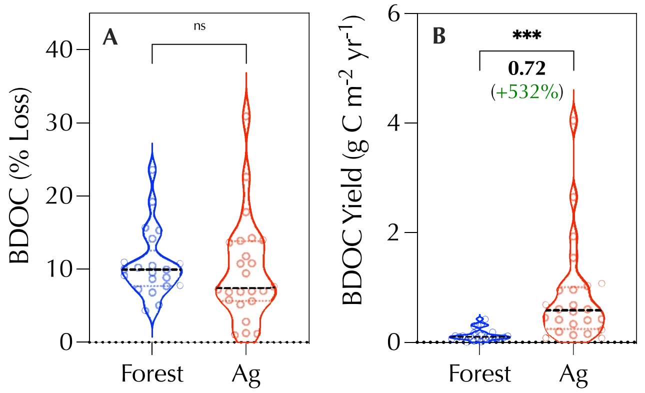

Figure 6. Violin plots of Biodegradable Dissolved Organic Carbon (a) and yield of BDOC (b) for the Forest (Blue) and Agricultural (red) streams sampled during baseflow conditions. For each panel, the Forest versus Agricultural unpaired *t*-test p-value summary (stars), average difference, and the percent difference are shown. Non-significant differences are denoted with a "ns".

BDOC proportions ranged from 4% to 24% and 1%to 31% for the Forest and Ag sites, respectively (Figure 6a). There was no statistical difference between the means of two sites (11% and 10%, respectively). These average BDOC values are comparable to values from streams in Eastern Congo (5%–20%) that varied by forest extent (Drake et al., 2019). The similarity in BDOC values between the Forest and Ag sites is unsurprising given the similarity in DOM composition (see section above on C:N ratio and DOC isotopic signatures), since DOM composition has been shown to control biolability (Findlay & Sinsabaugh, 1999; Marschner & Kalbitz, 2003). Despite the similar proportions of BDOC (as a percent), the yield of BDOC was significantly higher in the Ag stream compared to the Forest (difference of 0.72 g m^{-2} yr^{-1} or 532%, Figure 6b). This is due to the higher average DOC concentration and the higher water yields exhibited by the Ag stream.

3.5. Overall Effect of Agricultural Land-Use on C Export

Using the MODIS derived average NPP values of 214 and 176 g m^{-2} yr^{-1} for the Forest and Ag catchments, respectively, our results indicate that the Forest and Ag catchments export 2.0% and 8.9% of annual NPP as OC, respectively. Given the shared modern C3 soil and litter OC source between the two catchments, it appears that simply a higher proportion of NPP is leached and exported into the river system in the Ag stream. In other words, agricultural land use shifts a larger proportion of NPP to the river network prior to respiration. This is likely driven by the higher water yield in the Ag catchment and perhaps additionally by the sparser vegetation cover, which may be less effective at trapping sediment and intercepting rainfall and thus allow for higher rates of POC mobilization and DOC leaching compared to the Forest. Interestingly, unlike the heavily deforested and permanent agricultural catchments of Eastern DRC, which yield less but much older DOC than their forested counterparts (Drake et al., 2019), it appears that the shifting lowland agricultural landscapes around Kisangani contain sufficiently high amounts of secondary forests to sustain a high C yield. These high yields might be expected to decrease and reflect those of Eastern Congo as more of the catchment area is devoted to cropland or the cultivation cycles become shorter.

Depending on the proportion of excess NPP (i.e., additional NPP that is exported to Ag streams compared to Forest) that would have been respired versus sequestered in soils in the Forest, the higher OC yield from the Ag catchment could indicate a reduction in overall Net Ecosystem Production (NEP). Indeed, rivers have recently been recognized as strongly heterotrophic environments that process OC and outgas significant quantities of CO_2, suggesting that a large proportion of OC delivered to aquatic networks is ultimately respired (Battin et al., 2023). The higher CO_2 concentrations, CO_2 yields, and BDOC yields observed in this study could indicate that the Ag stream respires more OC than the Forest stream. On the other hand, if the excess NPP escapes mineralization and is buried in downstream aquatic environments, then the higher OC yield from the Ag catchment may in fact increase C sequestration. This process of transferring recently photosynthesized OC to depositional environments where it is less vulnerable to microbial respiration has been found to form a sink along the Land-to-Ocean Aquatic Continuum (Sanderman & Berhe, 2017; Van Oost & Six, 2023). In the case of the Ag stream, the higher concentrations and yields of CH_4 (Figures 4c and 4f) suggest that at least a fraction of the OC that is transiently buried within the streambed is anaerobically decomposed rather than stored. Ultimately, the stability and physicochemical condition of the depositional environment will dictate the proportion of OC lost to microbial processes.

Additional studies into the rate of C accumulation or loss in the biomass and soils of these catchments are needed to fully constrain the effect of the higher OC yields in the Ag catchment. Regardless, this study clearly shows that the proportion of NPP that is exported to streams is dramatically higher in agricultural landscapes and that proper accounting of agricultural land-use on C budgets needs to include lateral fluxes to the aquatic network.

4. Conclusion

Although limited to only two paired catchments, this study shows concentrations and yields of C to streams are significantly higher in agricultural compared to forested landscapes, while neither the composition nor source of this C differed between the two sites. A major driver of this higher yield is the higher specific discharge in the Ag

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catchment due to the loss of forest cover and the resulting reduction in evapotranspiration. In the case of DOC and POC, the higher yields were further augmented by the higher C concentrations. These results suggest that despite the higher water throughput in the Ag catchment, OC material is more readily mobilized, perhaps by an enhanced exposure of soil and litter to rainfall. The lack of a difference in $\delta^{13}C$ or F_{mod} of the OC in the Ag stream suggests that older (lower F_{mod}) and more ^{13}C enriched SOC is not being eroded by the higher rates of sediment transport. Instead, the OC exported to both streams is sourced from similarly young soil or litter-derived organic matter. Likely owing to the similarity in OC composition to the Forest stream, the Ag stream did not exhibit any difference in BDOC proportion. These findings are partially qualified by the sampling bias toward baseflow conditions, which may not reflect the same C that is exported during stormflow. Nevertheless, these results indicate that agricultural land-use may significantly increase the proportion of NPP (DOC/POC), DIC, CO_2, and BDOC that is exported to streams, thereby strengthening the linkage between terrestrial and aquatic systems. As more of the Congo basin's lowland forests are converted to agricultural plots, the transfer of C to rivers and the amount of C exported by rivers can be expected to rise. The fate of this material, along with the potential reduction in C inputs to soils, should be further investigated and constrained in order to resolve the overall effect of this larger C export from deforested croplands of Central Congo.

4.1. Global Research Collaboration

This study was conducted by collaborators within the Congo Biogeochemistry Observatory (CBO), an international consortium of biogeochemists hosted at numerous institutions which has partnered with universities and governmental researchers in Democratic Republic of Congo for nearly a decade (www.congo-biogeochem.com). Research permits for work in the Yoko Forest Reserve and the Balifi village outside of Kisangani were obtained through the provincial Ministry of the Environment of the Democratic Republic of the Congo via a collaboration with the University of Kisangani (UNIKIS) and the Centre pour la Surveillance de la Biodiversité (CSB) under the FORSEDCO II project. Local coordination, sample collection, and processing were conducted by the two UNIKIS students and co-authors SA and NB.

Data Availability Statement

All data are available at: http://doi.org/10.5281/zenodo.8258202.

Acknowledgments

We would like to thank the villages of Yoko and Balifi for their hospitality and cooperation on this project. We also thank Héritier Ololo Fundji for his assistance and on-site support. We are also thankful to Britta Jahn-Humphrey at ETH Zurich for her assistance with sample analyses. This project was funded by the ETH Core Funding of Johan Six with additional support from the FORSEDCO II project funding by the Fonds de la Recherche Scientifique–FNRS (grants T.0059.18 and J.0167.19). Open access funding provided by Eidgenossische Technische Hochschule Zurich.

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